TAMPERE UNIVERSITY OF TECHNOLOGY

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DESIGN FOR MANUFACTURING AND ASSEMBLY RULES AND GUIDELINES FOR ENGINEERING

Master of Science Thesis

Examiner: Professor Asko Riitahuhta

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ABSTRACT

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Companies' competitiveness can be improved either by optimizing production processes or by developing a product and components to fit better to existing production processes. The latter is sought by designing a product so that previously encountered production and manufacturability anomalies can be avoided. Various *Design for Manufacturing and Assembly, DFMA*, -methods are developed to design better and more easily manufacturable products.

DFMA methods are used to simplify the product structure, to reduce manufacturing and assembly costs, and to analyse and identify improvement targets. DFMA has evolved over time to become a philosophy of optimizing the total product from the standpoint of assembly, part design and total life cycle cost. The practice of applying DFMA is to identify, quantify and eliminate waste or inefficiency in a product design. Early consideration of manufacturing issues shortens overall product development time, minimizes development costs, and ensures a smooth transition into production.

Thesis was written in cooperation with Sandvik Mining and Construction. The thesis project was initiated because variable rules and guidelines to aid manufacturing and assembly existed in different production and development units at the company. There was no common practice in utilising DFMA for designing and engineering. As a result, it was seen that general guidelines to harmonize design practices were needed. Accordingly, the objective of the thesis was to create and initiate a first version of a common DFMA rules and guidelines for the company. Work was conducted in collaboration with three main Product Development Centers, Tampere (Finland), Turku (Finland) and Zeltweg (Austria).

Company offers a wide range of products and thereby rules and guidelines were designed to consist of both generic and product specific sections. Furthermore, design instructions were divided into concept and detail design sections to efficiently support product designing and to emphasise the importance of early design decisions. The DFMA rules and guidelines aim to compile and share best design practices among different Product Development Centers in order to harmonize product designing. Moreover, DFMA seeks to enhance collaboration practices between design and production departments to enable better product design.

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Tuotantoprosessien kehittäminen on tapa parantaa yrityksen tuottavuutta. Tuotteiden valmistettavuus luodaan kuitenkin pitkälti jo tuotteiden suunnitteluvaiheessa. Eri lähteistä riippuen on arvioitu, että valtaosa noin 70–80% aiheutuvista valmistuskustannuksista lukitaan jo tuotteita suunniteltaessa. Näin ollen tuotesuunnittelussa pystytään kaikkein laajamittaisimmin vaikuttamaan tuotteen valmistettavuuteen ja syntyviin valmistuskustannuksiin.

Lukuisia valmistettavuuden suunnittelumenetelmiä on luotu tukemaan tuotekehitysprosessia, esimerkkinä Design for Manufacturing and Assembly, DFMA-menetelmä. Menetelmät pyrkivät ennakoivasti optimoimaan ja huomioimaan halutut valmistusosa-alueet tuotesuunnittelussa, kuten valmistus-, kokoonpano-, testaus-, hankinta-, huolto- tai kuljetusnäkökulmat.

Tämä diplomityö lähti liikkeelle Sandvik Mining and Constructionin tarpeesta kehittää tuotteidensa valmistettavuuden ja kokoonpantavuuden huomiointia suunnittelussa. Työn tavoitteeksi asetettiin luoda ensimmäinen versio suunnittelijoiden käyttöön tulevasta DFMA-ohjeistuksesta. Laajempana tavoitteena työssä oli luoda pohja mahdolliselle suunnittelun ohjeistukselle, jota voitaisiin myöhemmin laajentaa koskemaan useampia tuotteiden suunnittelun ja valmistettavuuden kannalta oleellisia osa-alueita. Esimerkkeinä mainittakoon tuotteiden testattavuus, huollettavuus ja kuljetusnäkökohdat. Lisäksi ohjeistuksella haluttiin pyrkiä yhtenäistämään vaihtelevia suunnittelukäytäntöjä ja jakamaan tietoa parhaista käytännöistä eri suunnitteluyksiköiden kesken. Valmistettavuuden ja kokoonpantavuuden suunnitteluohjeistuksesta haluttiin mahdollisimman selkeä ja helppokäyttöinen. Työ tehtiin pääosin Sandvikin Tampereen tehtaalla, mutta työssä pyrittiin huomioimaan mahdollisuuksien mukaan myös Turun ja Zeltwegin (Itävalta) tehtaiden tuotteistoa ja suunnittelua.

Työn tuloksena syntyi alustava DFMA rules and guidelines -ohjeistus yrityksen myöhempään jatkokehitykseen. Aika- ja resurssirajoituksista johtuen pääpaino asetettiin tuotteiden asennettavuuden huomiointiin suunnittelussa. Ohjeistuksessa hyödynnetään lukuisia tarkistuslistoja ja yleisiä suunnitteluohjenuoria, sekä esitetään esimerkinomaisesti suositeltuja suunnitteluratkaisuja. Tavoitteena on korostaa valmistettavuuden huomioinnin merkitystä suunnittelussa ja erityisesti pyrkiä tehostamaan tuotannon ja suunnittelun välistä yhteistyötä läpi tuotesuunnitteluprojektin. Osana projektia pyrittiin arvi-

oimaan myös laajemmin DFMA:n hyödyntämismahdollisuuksia kohdeyrityksessä. Lisäksi luotiin prosessikuvaus ja suunnitelma DFMA:n laajemmalle käyttöönotolle kohdeyrityksessä.

Merkittävimmät tuotteen valmistettavuuteen vaikuttavat suunnittelupäätökset tehdään jo hyvin varhaisissa suunnitteluvaiheissa. Tästä esimerkkinä varhaisen vaiheen tuotearkkitehtuuripäätökset määrittelevät hyvin pitkälti tuotteen kokoonpantavuuden. Suunnitteluohjeistuksessa haluttiin näin ollen korostaa varhaisen tuotesuunnittelun merkittävyyttä ja kauaskantoisia vaikutuksia. Ohjeistus jaettiin varhaisia tuotesuunnittelun edustavaan konseptisuunnitteluosioon ja yksityiskohtaisempaan komponenttien ja alikokoonpanojen suunnittelua tukevaan osioon. Lisäksi ohjeistus jaettiin edelleen geneeriseen, kaikkia tuotteita koskevaan yleiseen osioon ja tuotekohtaiseen osioon. Jaottelu tehtiin helpottamaan ohjeen käyttöönottoa ja myöhempää jatkokehitystä eri tuotekehitysyksiköissä.

Suunnitteluohjeiden yksityiskohtaisuuden tason määritys ja toisaalta yleinen hyödynnettävyys asettivat omat haasteensa. Pitkälti yksinkertaistetut ohjeet ovat usein luonteeltaan liian yleisiä ollakseen tehokkaasti suunnittelutyössä hyödynnettävissä. Hyödyllisen suunnitteluohjeen tulisi olla konkreettinen ja tapauskohtainen, mutta toisaalta samaan aikaan ohjeen tulisi olla riittävän yleinen, jottei ohjeistuksessa rajoituta vain tietyn suunnittelukohteen standardointiin. Valmistettavuus- ja asennettavuustieto on usein hyvin tapauskohtaista, eikä siten helposti puettavissa yleiseksi säännöksi. Lisäksi valmistustietous on pitkälti sirpaloitunut ympäri organisaatiota, eikä sen esiin kaivaminen tai dokumentointi ole useinkaan kovin helppoa tai yksiselitteistä. Vakiintuneet ja syvälle juurtuneet organisaation toimintatavat asettivat myös omat haasteensa ohjeistuksen kokoamiselle. Tuotanto-organisaatio on perinteisesti tottunut antamaan palautetta tuotteiden valmistettavuudesta prototyypin tai varsinaisen tuotteen perusteella. Suunnittelulle etukäteen esitettävien omien toiveiden ja vaatimusten esittämisestä ei sen sijaan ole niinkään kokemusta. Palautetta on perinteisesti annettu lähinnä huonoista suunnittelumuutoksia vaativista kohteista, ei niinkään hyviksi koetuista suunnitteluratkaisuista. Työssä havaittiin selkeä mahdollisuus tuotannon ja suunnittelun välisen yhteistyön kehittämiseen DFMA-menetelmää hyödyntäen.

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Tommi Lahtinen

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ABBREVIATIONS AND NOTATIONS

Assemblability	Describes the easiness of an assembly job.
Cross-functional team	Group of people with different functional specialties or multidisciplinary skills, responsible for carrying out all phases of a program or project from start to finish.
CAD	Computer Aided Design. Uses the computer technology for the process of design and design-documentation.
CPE	Current Product Engineering. Design organization, which is responsible to maintain existing products.
DFA	Design For Assembly. DFA takes into consideration possibilities and limits of assembly processes and aims at designing assemblies or products that are easy to assemble and produce.
DFM	Design For Manufacturing. DFM takes into consideration possibilities and limits of certain manufacturing processes and aims at designing parts which are easy to fabricate and produce.
DFMA	Design For Manufacturing and Assembly. In this thesis DFMA is used as general term to describe all different DFM and DFA methods.
DFX	Design For eXcellence. DFX method aims to take into consider all internal and external customer requirements in product designing.
ERP	Enterprise Resource Planning. Integrated software which typically includes manufacturing, supply chain management, financials, projects, human resources and customer relation management.
Interface	A border that separates a component, sub-assembly, or module, and through whose two of them are interconnected.
Know-how	Know-how is practical knowledge of how to get something done.

LHD	Load Haul Dump. A vehicle used in underground mining.
NPD	New Product Development. Design organization, which is responsible to conduct new product design projects.
PDC	Product Development Center. Sandvik Underground Mining and Construction site, where both production and product development activities are represented.
PDM	Product Data Management. Integrated software which is responsible for the creation, management and publication of product data.
SOP	Standard Operating Procedure. An SOP is a written document or instruction detailing all steps and activities of a process or procedure. SOP's main purpose is to enable process monitoring and development.
Tacit knowledge	Knowledge that is difficult to transfer to another person by means of writing it down or verbalizing it. The opposite of tacit knowledge is explicit knowledge.
R&D/E	Research, Development and Engineering department at Sandvik Underground Mining and Construction.
UGM	Underground Mining one of the customer segments of Sandvik Underground Mining and Construction.
QFD	Quality Function Deployment is a method to transform user demands into design quality, to deploy the functions forming quality, and to deploy methods for achieving the design quality into sub-systems and component parts, and ultimately to specific elements of the manufacturing process.

1 INTRODUCTION

This thesis concerns design rules and guidelines for engineering to ensure and serve better products manufacturability and assemblability. It was written in cooperation with Sandvik Mining and Construction. In heavy machinery industry, a production process takes up a considerable amount of costs and resources, including production facility, human resources, information management and material costs. Significant part of these costs is committed in an early product designing phase. Early design decisions create a ground for later decisions and, therefore, the manufacturability of a planned product is largely founded during these design phases. Designing is the function which determines a lion's share of the costs in a product's life cycle. Accordingly, a company's productivity and profitability are largely based on the work of these engineering functions.

Design For -methods have been developed to aid various designing aspects and areas. The methods provide a systematic way to evaluate, rationalize and improve designing work. *Design For Manufacturing and Assembly, DFMA*, is one of these methods to systematically rationalize product development and improve easiness of a product's processibility. For instance, some desired impacts of DFMA utilisation are: less parts and documents to design, less complexity, reduced material costs, less parts to receive, inspect, store and handle, simpler assembly instructions, reduced lead time, reduced time for marketing, faster ramp-up, enhanced product quality, and higher profit margin. When correctly used, DFMA methods are powerful tools that provide far-reaching positive consequences and benefits for product designing.

Thesis was initiated because variable rules and guidelines to aid manufacturing and assembly existed in different production and development units at Sandvik Underground Mining. There was no common practice defined to utilise DFMA for designing and engineering. As a result it was perceived that a collective way to harmonize design practices and guidelines was needed. Furthermore, the scope of the thesis was defined to include following tasks: to create a first version and set a basis for later development of the DFMA rules and guidelines, to review and compile effective design principles in order to harmonize design practices, to evaluate DFMA capabilities in current and in future processes and to create an implementation plan for the DFMA.

Research process followed mainly a Design Research Methodology presented by Blessing and Chakrabarti [Blessing & Chakrabarti 2009], see figure 1.1. Study was initiated with literature review. DFMA and DFX were studied by using existing literature as the key source. Empirical data was collected with questionnaires and multiple discussions and interviews with various company representatives were held to obtain an understanding of the product development and production processes, see Appendix 2.

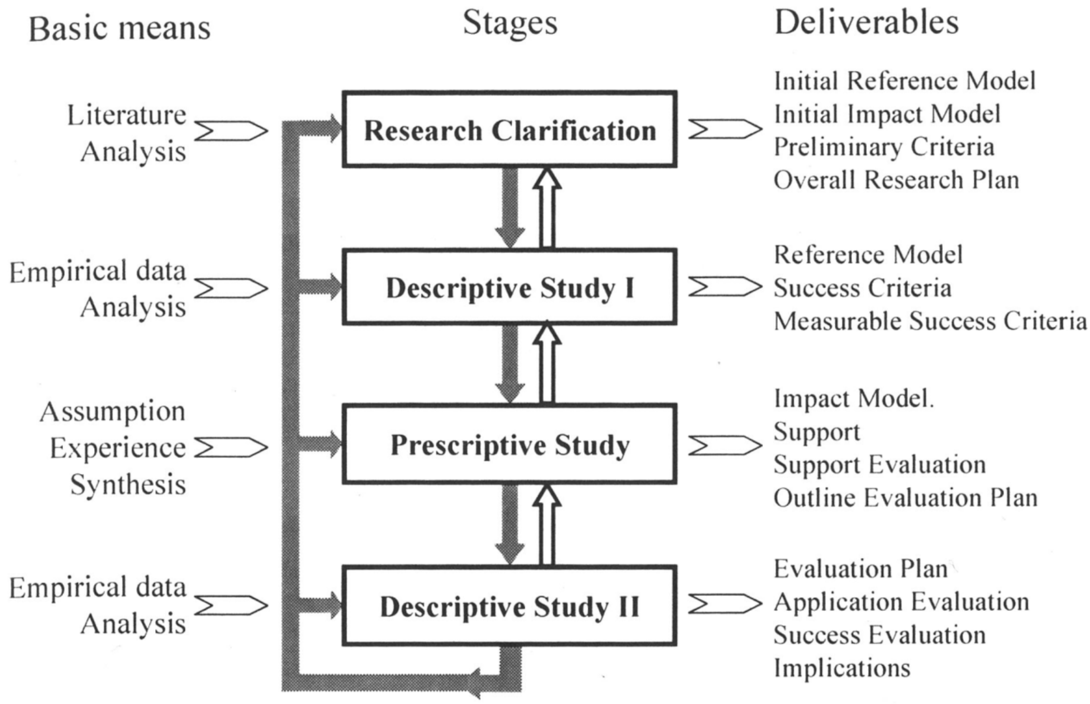

Figure 1.1. Design Research Methodology framework: stages, basic means and deliverables. [Source Blessing & Chakrabarti 2009, p.38]

Furthermore, DFMA guidelines creation was first approached by exploring typical assemblability problems of current products. Assemblability and manufacturability problems were surveyed by multiple discussions and interviews and by practical work internship. The interviews were conducted informally, in a qualitative manner, allowing the interviews to explain and clarify the cases and topics as seemed most appropriate. Critical sub-assemblies were identified and manufacturability and assemblability issues were examined. After these reviews, the focus was shifted to the creation of common DFMA guidelines in collaboration with various engineering departments. The objectives of these guidelines were set to be applicable and easily usable. According to these objectives, it was soon clear that the actual challenge lay in the focus level of design rules and guidelines. To be actually helpful in designing instructions should make a statement about detail level considerations, but at the same time instructions should be widely utilisable and easy to use. In addition, the level of detail was restricted by the project's schedule and resources. Especial attention to the structure of the DFMA instruction was thus needed. The DFMA rules and guidelines were divided into two main categories: concept and detail level design guidelines. This was done to emphasise the importance of early design decisions. Moreover, multiple design examples and best design practices were presented in form of case studies to draw attention to these aspects and to unify design principles.

The DFMA rules and guidelines are meant to be used primarily on *New Product Design, NPD*, but additionally it should also be utilised on *Current Product Engineering, CPE,* projects. The scope was restricted to include only Sandvik's customer segment of Underground Mining. More specifically, the following production sites and Product Development Centers were examined: Tampere (Finland), Turku (Finland) and Zeltweg (Austria). The functions included in the project were Supply and Research & Development and Engineering functions. Mechanical, hydraulic, electrical and automation engineering departments were included from all three Product Development Centers. Because of resource constraints the main priority of the thesis work was focused on a product's assemblability issues. Assembly was prioritised, since it was discovered that it can provide most promising development opportunities. Simultaneously there was an ongoing company-wide large-scale lean project, focusing on the development of production efficiency. Company wanted to enhance productivity both by rationalising production operations and by improving product designing.

The thesis is divided into six chapters. The second chapter describes the theoretical background of the thesis work. Product development is discussed in general terms, the meaning of early design phases is outlined, the evolution of Design For -methods is introduced and the DFMA method is presented and discussed in more detail. The second chapter ends with a discussion of implementation of DFMA. Necessary decisions and training needed for efficient implementation of DFMA are discussed and some possible challenges that DFMA implementation may encounter are described.

Company presentation is given in the third chapter. The company's main business, products and current production of Underground Mining machines at Tampere, Turku and Zeltweg factories are presented. Sandvik's Offering and Product Development Process is also described.

The fourth chapter discuss how DFMA could be utilised at Sandvik Underground Mining context. The need for the DFMA and practical utilisation possibilities are discussed in this chapter. Moreover, the DFMA rules and guidelines created as a result of thesis is introduced and discussed from the salient points of view.

Conclusions are presented in the fifth chapter. Further development ideas and recommendations for the continuation of the DFMA implementation in the company context are discussed in the sixth chapter.

2 THEORETICAL BACKGROUND

The theoretical background related to thesis is presented in this chapter. First, the levels and hierarchies of product development process are described as well as their role in company context. Second, the meaning of early design phases is discussed and emphasised. Third, *Design For -methods* are generally introduced. Fourth, DFMA method is described in more detail and miscellaneous issues related to DFMA guidelines are discussed. Fifth, practical DFMA implementation matters are discussed.

2.1 Levels of product development process

Danish Institute for Product Development has presented that a company's product development can be divided into four different designing levels: corporate level, family level, structural level and component level. The meaning of this break down structure is to emphasise the development of the procedure concerning reuse of technologies, principles, sub systems and components across a company's products and product families. All proposed product designs have implications on all four levels, whether they are considered or not. [Fabricius 2003]

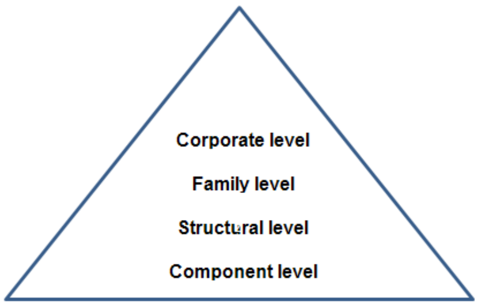

Figure 2.1. *Levels of product development process*

The highest of the four presented designing levels is corporate level. Corporate level leans on to the company's strategic and therefore is closely related to the company's production policy. Large and long lasting decisions concerning product range are made on this level. On the corporate level, designed products and company's other products are compared. The aim is to ensure that similar products are not produced in different sections of the company and thus avoid overlapping product range. Moreover, the intention is to ensure that the same solutions are used to the same problems. Fragmented and wide product range can cause many challenges, especially in companies which has grown rapidly organizationally or by acquisitions and mergers. For these reasons corporate level can provide tremendous opportunities for design improvements.

Good solutions here can cause a positive cascade effect by eliminating large amount of structural and component related problems. For instance, redundant old items and products can be reviewed and eliminated regularly. Product range harmonization projects and regular reviews may have far-reaching positive effects. However many practical problems are related to this level. Most of all, there is a possible lack of responsibility. Often the design implications are given little consideration, since it is above the typical responsibility of the project leader of the development project. [Fabricius 2003, p.8–10]

Product family level considers on the relationship between the different variants in the same product family. Different products in the product family are compared and their variation is evaluated. Often product life time is also defined and marketing plans are created on this phase, how to introduce different product variants to the market. Family level aims to avoid situation on which products are highly tailored without an overall picture. Products may vary a lot and new features and sub-systems are hung with little consideration to either logistics or indirect manufacturing costs. Family level works as a base for new product development. For instance new product could be developed by scaling existing products to more efficient and powerful, by exploiting efficiently the possibilities of modular product structure. Gained special knowledge of own production techniques, methods and know-how should be efficiently utilised and distributed among product development projects. [Fabricius 2003, p.8–10]

On the structural level the aim is to achieve an understanding how product's structure and production process fit together and how this relationship could be developed. The designer can use a known production bottleneck functions as a design basis to find new structural solutions in new product development. For instance product testability could be simplified by combining product structures to sub assemblies. Therefore product structure level focuses on the relationship between the different sub systems and components. The internal cost distribution can be used to reveal the sub assemblies and components that are the most critical ones, where design improvements might have the biggest impact for manufacturing costs. Benchmarking might be used to determine in which areas the manufacturing process differs critically from world class performance. [Fabricius 2003, p.8–10]

Component level focuses on the design of each individual component. The component level is the level, where detail level design decisions are made. It is also an area where everybody has an opinion. In order to save development time and recourses it is useful to concentrate on critical components in terms of cost, time, reject rate or other known problem related components. Scarce recourses have to be directed to the most expensive components and that might cause problems or are difficult to get. Components availability and outsourced component manufacturing need also some extra care. Supplier often has a more in-depth knowledge of the manufacturing operations, than the producer and thus it have to be confirmed that this knowledge is utilised and also outsourced components will be taken into under development. Component level's primary target is to ensure the yield of components and make plans and design how to cover this required yield with reasonable low risk level. [Fabricius 2003, p.8–10]

2.2 The meaning of the early design phases

Large portion of a product's production costs is already determined in the design and development phases. Figures ranging from 70–80% of the product cost are often estimated and mentioned. However, this is only a rough estimate and it is obvious that the influence will vary depending on the type of product considered. [Erixon 1999, p.15]

These committed costs are called *locked-in costs* or *designed-in costs*, which are costs that have not yet been incurred but will be realized in the future on the basis of already made design decisions. Costs are committed with accelerating speed in early design phases with respect of early design decisions. Moreover most locked-in costs are determined in early design phases, when overall knowledge level of design is still relatively low. This information deficit is largest in early design phases, especially in concept design phase, when the most important decisions concerning product are made and largest portion of costs are locked-in. Following figure illustrates the origin of the information deficit graphically during design phases. [Horngren et al. 2005, p.382–384]

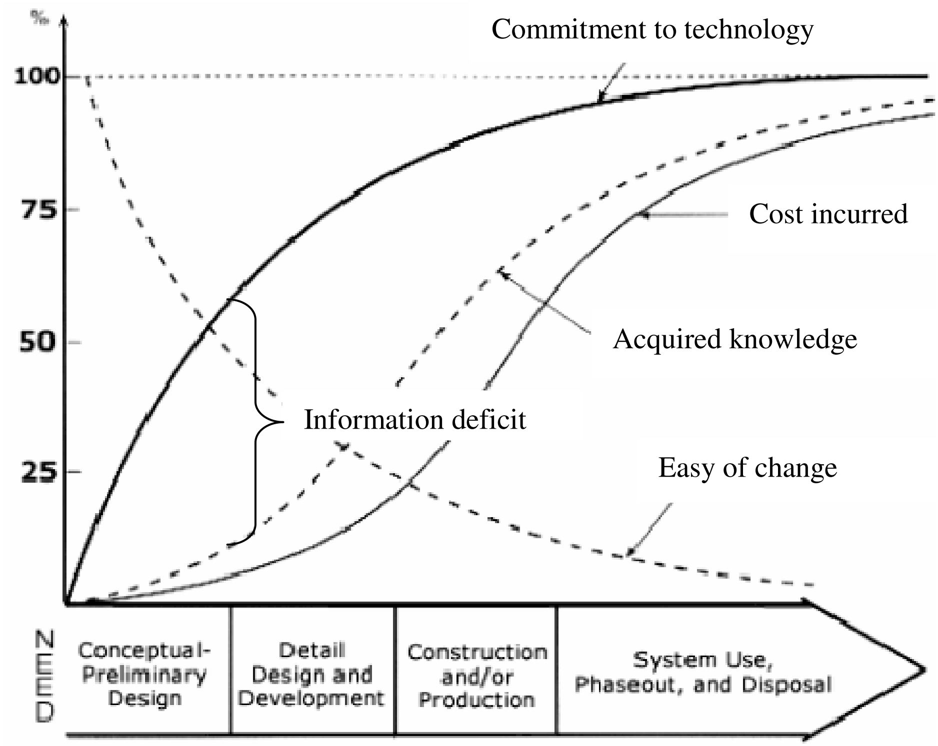

Figure 2.2. *Origin of the information deficit during product development process. [Modified from Lempiäinen & Savolainen 2009, p.15]*

The figure shows that the relative ease of design change decreases very quickly during early design phases. It is really important that all possible stakeholders both external and internal are considered and their product requirements are taken into account at the beginning of the project. The latter on design phase changes will be more costly and more difficult to carry out. Large product design changes can be avoided, by involving and considering all different stakeholders of a product development project at the very beginning of the project. *Design For -methods* and *DFX* are developed to provide systematic way to ensure all stakeholders early involvement and attendance to the design project. DFX methods provide the most benefit when they are applied early in the design process when changes are relatively easy to make. If DFX is delayed until detailed designs are well under way or finished, there will be too little money or time to make more than cosmetic changes. With DFX it is possible to share and spread information and best practices across the organization, achieve cost savings and improve product quality. [Lempiäinen & Savolainen 2009, p.14–16; Whitney 2004]

The manufacturability of a planned product is founded during the conceptual design phase. In the concept development phase, the needs of target market are identified, alternative product concepts are generated, evaluated and concepts for further development and testing are selected. According of Ulrich and Eppinger a concept is a description of the form, function and features of a product. It is usually accompanied by a set of specifications, an analysis of competitive products and an economic review. [Ulrich & Eppinger 2008, p.15]

Accordingly the concept development phase requires tremendous integration across the different functions on the development team. Institute of Product Development emphasis that one prerequisite for successful production rationalization is to create and define concrete guidelines to synchronize the collaboration between development and production departments during the critical conceptual design phase [Fabricius 2003, p.3]. Designing investigates feasibility of product concepts, builds and tests experimental prototypes in synchronization with production department, which estimates manufacturing costs and assess production feasibility.

However, in early design phases the amount of uncertainty is highest and the lack of information may be a problem. Without defined working procedures and guidelines different departments may be reluctant to give estimates of production costs or sales volumes. This may drive design team to a difficult situation, because they have to make decisions without clear consensus of the estimates. [Lempiäinen & Savolainen 2009, p.22]

Moreover, deficient interaction between production and engineering in early design phases may result that expensive or unfavourable design concept may be chosen and ended to a further development. Possible production problems are thus occurred and detected on late design phases, in prototype phase or in the worst case after the actual production has started. Traditional solution is to adapt production process to apply design or return design to engineering phase and fix detected deficiencies. This design iteration loop is however time taking and may cause delayed market entry, increase development costs or weaken manufacturability. These kinds of consequences are unwanted and as few engineering iteration loops as possible are preferred. [Huhtala & Pulkkinen, 2009, p.179–180]

Often with traditional product development models, product development time reduction is aimed by generating only a few concepts. In addition prototypes are rarely used and often in late design phases. Sought time reduction from critical concept design phases may cause many other problems, in form of locking designer hands too early to a certain design and restrict the search for new design solutions. Integrated product development models have been introduced to avoid this kind of problems and to emphasise the meaning concept design and concept comparison. Figure 2.3. presents the concept comparison model developed by Stuart Pugh in 1990. The main idea of the model is to ensure that a large number of concepts are first created and took under development. After concept creation these concepts are systematically screened and compared. After careful concept comparison the most promising concept are further developed and the best concept is chosen. [Huhtala & Pulkkinen, 2009, p.179–180]

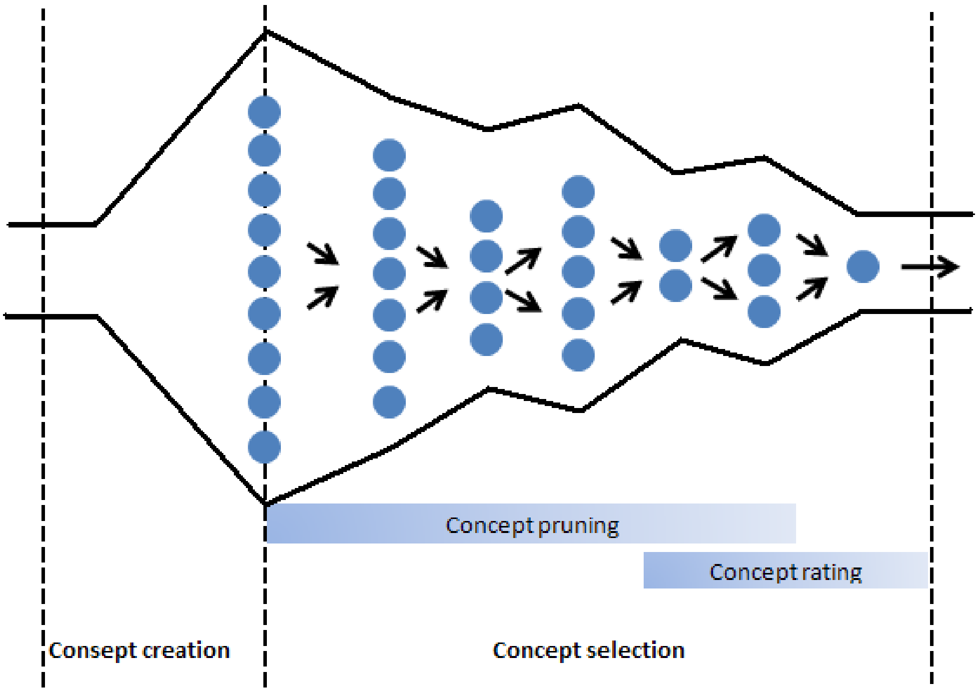

Figure 2.3. *Pugh's concept selection model. Concept design is illustrated as a development funnel, which narrows as concepts are pruned. Single ball in the figure represents a concept. [Modified from Huhtala & Pulkkinen, 2009, p.181]*

Moreover a systematic concept comparison should be comprehensive enough to ensure technical and economical evaluation of concepts. It should also be executed on a broad-based and whole manufacturability of the product should be represented and included to the evaluation. First of all evaluation of alternatives should be done during the conceptual design phase, because that is the design phase where engineers still have free hands to do design changes and affect to design outcome. Some manufacturing engineers may experience it uncomfortable to evaluate manufacturability before detail level drawings exists. However, even the estimates are still inaccurate, they might be sufficiently reliable for the needed relative comparison of alternative solutions. [Fabricius 2003, p.26]

Concept comparison is an efficient way to find and compare new solutions to engineering problems. Designers are faced with various difficult tasks and decisions and therefore it is easy to incline towards to focus on components and design details too soon. It is common to spend much time on trying to improve the manufacturability of a product by optimizing the component details on the expense of deciding the best suitable conceptual product design. This is an inappropriate work pattern since it focuses on too detail level problems too early and draws attention and resources away from conceptual issues. Too early focus on details may also pose designer to entirely overlook innovative design possibilities on the higher levels. [Fabricius 2003, p.5]

Whitney presents some common reasons why component details are too often defined in an inappropriate work pattern. He represent that CAD systems today bountifully supports design of individual parts. It thus tends to encourage premature definition of part geometry, allowing designers to skip systematic consideration of part-to-part relationships. Against CAD systems he also points out that most often the dimensional relations that are explicitly defined to build an assembly model in CAD are those most convenient to construct the CAD model and are not necessarily the ones that need to be controlled for proper functioning of the assembly. In additions he expresses that most textbooks on engineering design also concentrate on design of machine elements and parts rather than assemblies. [Whitney 2004]

2.3 The evolution of Design For -methods

One of the first manufacturers to deliberately focus design attention on the assembly process was Henry Ford, whose early cars had simpler designs and fewer parts than many of his competitors. In 1908 Ford introduced successful Model T, which was the first car produced on assembly line. Assembly line production was made possible, because manufacturability was considered on designing. Parts and components of Model T were designed and manufactured in a way that those were suitable for any Model T car. Parts joining and fastening methods were also considered in designing and made easy and quickly, to made line assembly production possible. To enable car production on assembly line, manufacturability and assemblability issues were thus needed to be considered on designing phase. Henry Ford realized that mass production in huge quantities could not be achieved until time-consuming fitting operations were eliminated. Interchangeability therefore became the route to rapid assembly, while retaining such life-cycle advantages as simplicity of field repair. This he accomplished by increasing the accuracy and repeatability of fabrication machinery. He then organized his assembly workers in teams, each of which built a large subassembly such as a dashboard. This proved too slow, however, because the workers spent too much time getting parts. So he organized the people and parts into an assembly line and brought the work and the parts to the people. At this point, production capacity exploded and the mass production age was born. [Liker 2004, p.20–22, Whitney 2004]

During the period between 1940's and 1970's many manufacturing companies experienced extreme growth. They were mass-producing products in few variants with focus on exterior design and functional issues rather than on manufacturing properties of the products. The design departments had no great pressure on focusing on easiness of manufacturability since the economy of the scale advantages were considered to minimise manufacturing costs. In 1960's increased labour costs forced companies to focus more on automatic assembly and several companies started to develop their own producibility guidelines. [Liker 2004, p.20–25] General Electrics, for example, compiled manufacturing data into one large reference volume, the *Manufacturing Producibility Handbook* (General Electric, 1960). The handbook was intended for internal use and to be utilised by designers as a quickly and easily available reference material. The main focus was to ensure that parts could be manufactured, assembled, and tested using current or readily available techniques and processes, while meeting performance requirements. Therefore the focus was in single part designing and little attention was given to the whole manufacturability and assemblability of a whole product or assembly. [Sage & Rouse 2008, p.523]

In 1970 Boothroyd and Dewhurst started their research and experiments of assemblability, (*Design For Assembly, DFA*). They researched how product's assemblability influences to assembly method and product costs. They researched what boundary conditions should be considered on product designing to make assembly work as easy as possible. According their research work Boothroyd and Dewhurst created generic design guidelines, to help design assembly friendly products. The main idea behind these guidelines was to simplify product structure and reduce part amount by consolidating parts and redesigning assemblies. In DFA researches it was discovered that products assembly time is a good meter to compare alternative designs. At that time basic design rules and guidelines were also collected and presented for instance by Pahl and Beitz's Systematic Engineering Design, which was first published in Germany in 1977. Manufacturability issues and assemblability friendly design was also concerned in this book. [Pahl & Beitz 1990]

Later on in 1980 perspective was expanded to cover whole product design, not only assemblability point of view. The aim was to match whole product's design requirements and constrains to fit with production and emphasise that these issues are considered in designing. Several methods and techniques were developed for this, like *Design For Manufacturability*, DFM and DFMA. These methods are introduced more detail later on. [Sage & Rouse 2008, p.524]

Recently more attention has been paid to product's environmental issues and effects. Moreover, interest towards product's whole lifecycle has arisen considerably. The focus has expanded to cover designing of disassembly, disposal and maintenance issues among others. In addition, to environmental issues newer and more and more important areas in product designing are: quality, reliability, serviceability and supply chain management considerations. Altogether, these issues and trends could be collected under *Design For eXcellence* -term, DFX, where the X stand for any kind of restriction or aim in designing work. Briefly DFX aims to take into consider all internal and external customer requirements in product designing [Eskilander 2001, p.23]. According to Erixon, DFX can be regarded as a goal focused activity with the purpose to fit the product to the life phase system [Erixon 1999]. Whitney adds that, each DFX represents a body of knowledge, procedures, analyses, metrics, and design recommendations intended to improve the product in the domain "X." [Whitney 2004]

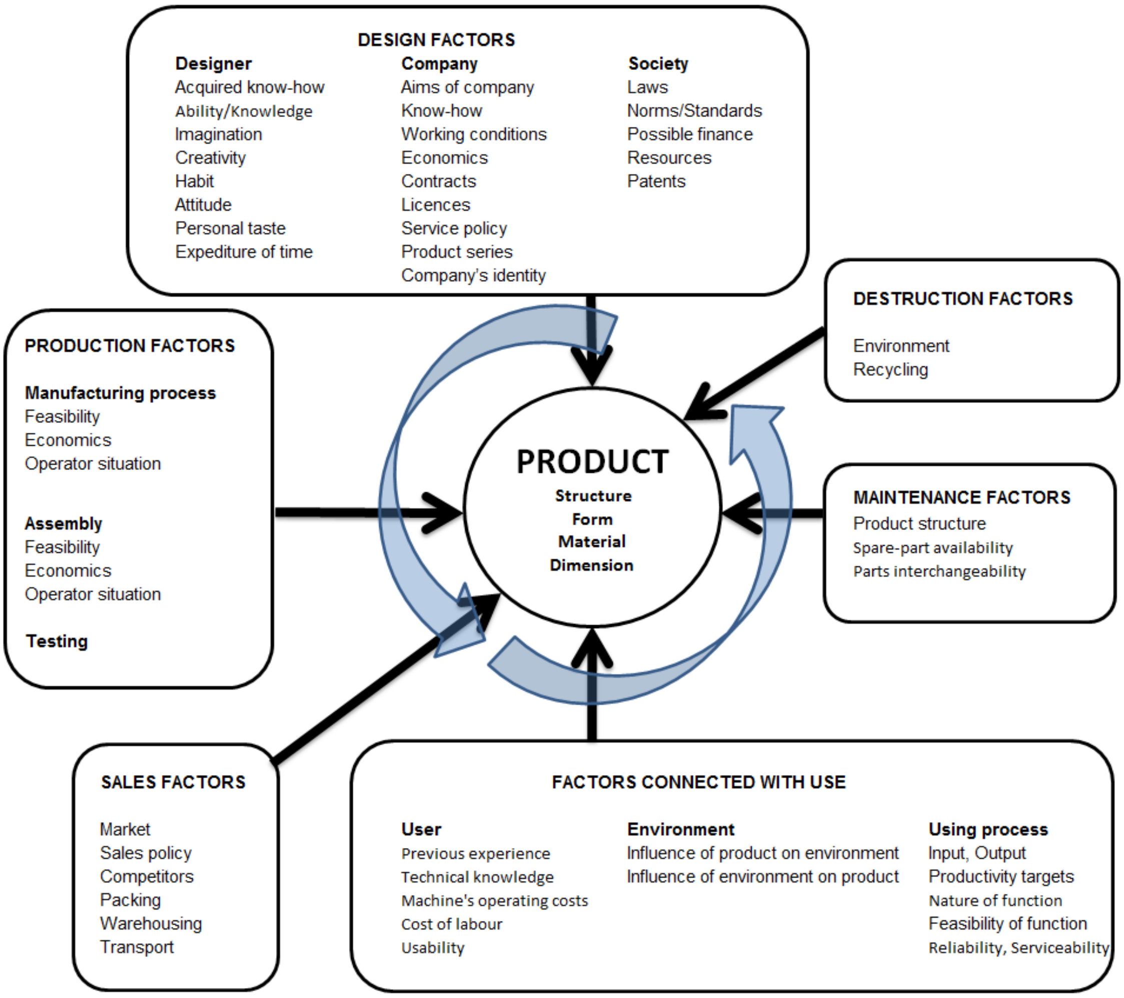

Figure 2.4. *Product factors in order of product's life-cycle phases. Product factors create a demand for product's basic characteristics, shown in the middle. Product factors can also be considered as DFX sub-diciplines according to Andreasen and Erixon. [Modified from Andreasen et. al. 1988, p.99]*

According to Andreasen DFX has two meanings, X may stand for product property or for a product life phase activity. Latter one is illustrated by the figure above. Generally the design of a product is a complex task and subjected to long list of varying requirements. The ultimate test for engineering is to make necessary trade-off decisions and to prioritize between colliding requirements. How well this compromise is done, depends heavily on the designer's ability to exploit acquired know-how and use his creativity. The crossfire of varying design factors and requirements is illustrated on the figure 2.4. [Andreasen et al. 1988, p.99–101]

2.4 Design for Manufacturing and Assembly, DFMA

One widely acknowledged factor for manufacturing companies' competitiveness is product designer's ability to understand the manufacturability of his product design. The designer will normally concentrate first and foremost on getting the product to function within the economic limitation laid down. Time is usually a limiting factor in designing. Consequently designers try to get the product detailed, so it can be moved to the production as soon as possible. If design process is not well coordinated and carried out in a hurry, the outcome is not optimal from manufacturing and assembly point of view. [Andreasen et al. 1988, p.68]

Design For -methods cope with these kinds of considerations. *Design For Manufacture, DFM*, *Design For Assembly, DFA*, and *Design For Manufacturing and Assembly, DFMA,* are all systematic methods to improve product designing.

These methods provide a systematic way to develop designing activities, in a way that manufacturability and assemblability have taken into consider. This is sought by designing a product in a way, that already known production and manufacturability anomalies can be avoided and thus productivity can be improved. Optimization of the assembly or component fabrication is rarely a goal itself. However there is a great need for early design tools that can assist in reaching high overall manufacturability and thereby improved the productivity and the competitiveness. [Huhtala & Pulkkinen, 2009, p.224]

DFMA methods are not exactly uniformly defined. In generally, all methods and arrangements which simplify product's production process and reduce whole product's manufacturing costs may be considered as DFMA. *In this thesis term DFMA is used generally to describe all these methods.* Commonly DFMA methods utilise recommendations, checklists and guidelines to contribute product development team to design more easily manufacturable products. DFMA methods and tools are not only restricted to pure manufacturing and assembly issues. Good manufacturability and assemblability have for instance far-reaching positive consequences into the product's testability, maintenance and serviceability. Moreover, DFMA could be exploited to design product more reliable, to fit better to its main purpose, to facilitate maintenance, looks neater or reduce the environmental load of the product. The effect of designing the product for ease of manufacture has often immense benefits compared to another rationalization means in production [Fabricius 2003, p.3]. After all, the primary objective of various DFMA methods is to reduce the total cost of manufacturing and achieve better productivity and profitability. [Lempiäinen & Savolainen 2009, p.13]

With DFMA methods it is possible to improve productivity without high capital investments. Fabricius presents that generally manufacturing companies have two main alternatives to seek cost reductions. Companies can lower the labour costs by increasing utilization of automation. This alternative provides many advantages if product is suitable for automation and production volumes are high enough. However this approach increases overhead costs and consequently needs machine investments. Another solution is to utilise DFMA methods by rethinking the product design and focus on to cut direct production costs by focusing on products that are ill-suited for automation. Consequently, in many cases DFMA designed products required less investment in automation. For example, in some successful DFMA projects the needed investment to automate of the assembly has been reduced 90%, owing to the DFMA focused design. Generally DFMA has been utilized most successfully, in cases where the present product has insufficient manufacturability, but a satisfactory marketability. [Fabricius 2003, p.6]

On the core of DFMA methods is the utilisation of gained manufacturing knowledge and know-how. Production department's feedback towards made design decisions is crucial on applying DFMA method. The manufacturability of a product can be improved by feeding gained manufacturing experience back to the design activity. Herby, the awareness and the understanding of the affects of made design decisions can be improved. Continuous linkage between design ideas and the resulting manufacturing consequences is pursued. [Fabricius 1994, p.15]

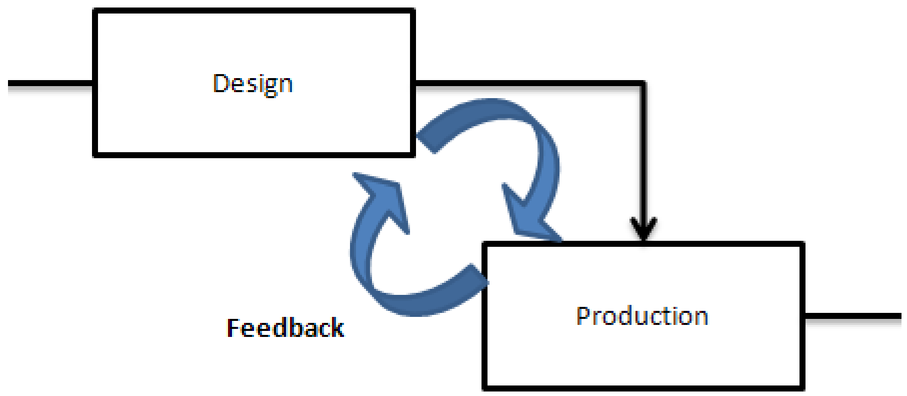

Figure 2.5. *Continuous feedback-loop between design and production functions is desired in DFMA. [Modified from Fabricius 2003, p.15].*

Systematically utilised DFMA method sets a framework for design improvement and helps design team to focus on clear and common objects. Moreover systematic DFMA method prevents manufacturing problems being shifted from one area to another. DFMA focuses on total costs and avoids sub-optimization. DFMA provides a better cost understanding and prevents shifting costs from direct to indirect costs. For instance, to avoid situations, where reductions in direct costs are pursued at the expense of overhead costs, product quality or lead time. DFMA methods also aim to allocate and utilise design recourses more efficiently in product development process. In addition DFMA methods emphasise the importance of early design phases and thus prevents to consume excessive amount of resources on product detail design on too early design phases. [Fabricius 2003, p.3]

Design easy to manufacture and assembly products require expert knowledge from wide and multiple different engineering areas. Collaboration and teamwork between different departments and function has a remarkable role and can be the key between success and failure. *Cross-functional teams* are integral part of the DFMA projects. DFMA projects utilises information of several types, including: sketches, drawings, product specifications, design alternatives, a detail understanding of production and assembly process, estimates of manufacturing costs, production volumes and ramp-up timing etc. Successful DFMA utilisation requires comprehensive contribution and expertise from wide area, including manufacturing engineers, cost accountants, quality inspectors, production personnel and product designers. [Ulrich & Eppinger 2008 p.211]

At very minimum, *a cross-functional team* consists of a design engineer and a manufacturing engineer, who work together throughout the whole product development process. The team meets regularly and are preferable located in the same room. The approach facilitates concurrent engineering and the manufacturing engineers become familiar with the design of the product. Some of the benefits are that manufacturing can more or less have a finished manufacturing system at the same time as the product is finished. Some drawbacks of this method are that designers may feel that the company does not trust them to create good design independently. Designers can feel upset that this new system undermines their creativity and that manufacturing's demands are often unrealistic, especially concerning wide clearance tolerances. The approach requires team members to gain broad expertise in producibility, since there is no longer one single expert in that area. [Eskinder 2001, p.31]

DFMA methods could also be used for benchmarking purposes. Using a DFMA analysis as a benchmarking tool can help companies to compare their products to competitors' products, and thereby find ways of closing eventual gaps between the products. Evaluation results can be used to compare alternative design solutions. Since alternative design solutions can affect assembly, manufacturing, purchasing, inventory and other overhead cost categories in conflicting ways, the comparison can many times be very valuable. [Eskilander 2001, p. 29]

2.4.1 DFMA approach and DFMA's place in product design

Several DFMA guidelines and generalizations have been presented as a way to design more production friendly way. Methods and techniques have highlighted the importance to design for easy to manufacture and assembly on detail level. Consequently, methods have mainly focused on the late detail design phases of the product development. Principles and methods have easily led to a situation which has focus on details, in form of single work steps streamlining. This way, the view of point to utilise DFMA techniques have become reactive in nature and ability to structural influence have been low. The resulting solutions have not reached the overall optimum. [Huhtala & Pulkkinen, 2009, p.15]

Top-down approach

To avoid described bias in design process, hierarchical DFMA methodologies have been developed. These DFMA methodologies emphasise the importance of holistic design process. Institute for Product Development from Technical University of Denmark have presented a DFMA methodology that operates on four hierarchical levels: company level, family level, structural level and component level. This DFMA method uses a *top-down approach*, first clarifying the design on corporate level, then on family level followed by structural level and finally on the component level. Top-down approach is used on designing, because decision on higher level provides the basis for lower level decision. Moreover, these high level decisions define substance amount of costs and form the basis for later on design. Herby, by solving or making one upper level decision multiple detail level problems might become obsolete or eliminated. This way top-down approach avoids untimely attention on product details and prevents to consume and waste excessive amount of resources on product details on too early design phase. [Fabricius 2003, p.8–11]

Herby, many DFMA methodologies emphasise the significance of early product development decisions and especially the meaning of conceptual designing. Successful DFMA utilisation in conceptual design phase normally leads to significantly simpler product structure and design. The aim is to consider manufacturability and assemblability issues and evaluate design consequences on early design phases. Consequently by eliminating major manufacturing problems already in conceptual design phase, when designing has not yet been locked-in and amount of design restrictions is still relatively limited. According to Institute for Product Development this type of DFMA typically requires more resources in the conceptual design phase, but this resource usage is compensated by shortening of the later design and development phases. The emphasised role of conceptual designing phase is justified, because the conditions like product variance and structure are determined in early product development process, which have a vital importance for the future production characteristics of the product. [Fabricius 2003, Huhtala & Pulkkinen 2009]

However, more traditional approach to DFMA often focuses on cost reduction through optimisation of components in relation to the actual production process and the assembly. Institute for Product Development has presented that the reason for these divergent approaches might be a different background or the origin of the mindset. Is the design's rationalization mind-set origin from the design engineering or from the manufacturing side? All in all, no matter what is the origin, designers must learn to work with coherence between the product design and the manufacturing method. The continuous linkage of design ideas and the resulting manufacturing consequences is one of the most important elements in designing competitive products. [Fabricius 2003]

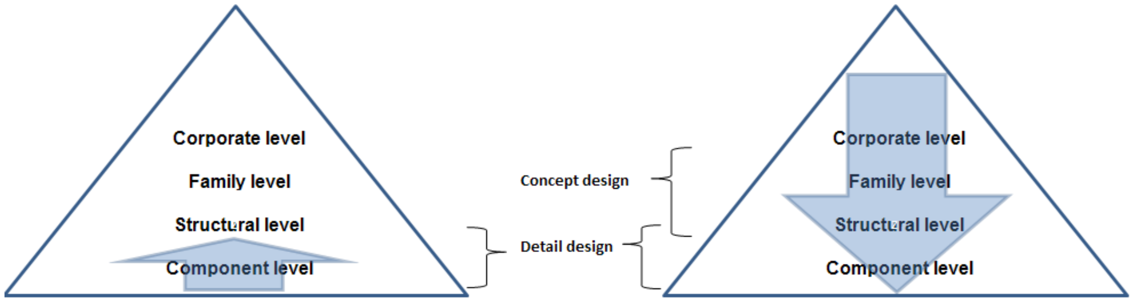

Figure 2.6. *The principle idea how down-top and top-down DFMA-approaches diverge. Conceptual and detail design phases have been drawn to the picture to indicate where they have the largest influence.*

The figure above described two different backgrounds owning approaches for production rationalization. On left hand side the cost reduction is pursued through optimisation of components in relation to the actual production process and the assembly. This approach has it background on the production side and thus may seek to modify product characteristics to fit better for the current production system. For instance: "*Current production line can be utilized more efficiently if we use the following product design"*. This approach is suitable for current products production rationalization projects. However, the effect of this approach is more restricted if the rationalization is limited to detail level design decisions and improvements.

On the right hand side there is presented top-down sequence according to Institute for Product Development. Top-down approach seeks large and far-reaching design effects and thus it fits best for the situations where large design changes or totally new products are designed. The approach has is background on the design engineering side and it emphasises the importance of concept designing. For instance, decisions affiliating on product structure or variance. *"By utilizing modular design we can improve our productivity"*. This model uses top-down sequence to for design rationalization. By solving one upper level problem, it may result in elimination of multiple detail level problems at the same time. Decision on higher level provides the basis for lower level decision. However, it is clear that upper level design decisions are more difficult to reach and affected by. Corporate and product family level design decisions are highly remarkable and committing by nature. [Fabricius 2003, p.10]

Whitney's approach: DFX in the Small and DFX in the Large

Whitney presents another approach to apply DFMA or more widely DFX to product designing. He emphasises that product architecture and technology have large implications for how a product will be assembled. Many aspects of product design and development are strongly related to assembly or make themselves felt when assembly-related issues are brought into the product design process. The most important of these is product architecture, which defines the physical relationships between elements of the product and relates them to the product's functions. A suitable architecture is an enabler of many important processes from product development to management of variety.

Thereby Whitney divides DFX methods into the following two categories: [Whitney 2004]

- *DFX in the Large* deals with issues that require consideration of the product as a whole, rather than individual parts in isolation, and likely will require consideration of the context in the factory, supply chain, distribution chain, and the rest of the product's life cycle. In other words it focuses on the methods or process steps that involve consideration of all the parts in an assembly at once and that may need many people to interact.
- *DFX in the Small* focuses on methods or process steps that can be applied to one part at a time by an engineer working alone. For example simplifying the feeding, orienting, and inserting of individual parts. It does this by various means that involve classifying the parts or the assembly actions required, and then scoring or timing them approximately according to the classification.

By this division into two separate categories Whitney emphasises that it is important to understand when DFX recommendations can be applied by an engineer working alone and when the interests of others, both technical and nontechnical, must be considered. Moreover, Whitney points out that for example some DFMA recommendations can conflict with each other. Generally, recommendations arising from DFX in the small are less likely to encounter conflict with each other while those arising from DFX in the large, especially when they affect product architecture, are more likely to encounter conflict.

DFX in the small is reasonably easy to separate from other design processes, but DFX in the large is hard to separate from product architecture and product design overall. Following figure 2.7 attempts to compare these different topics and to lay them out in approximate temporal order with the understanding that there is usually a lot of iteration among them as a product is being designed.

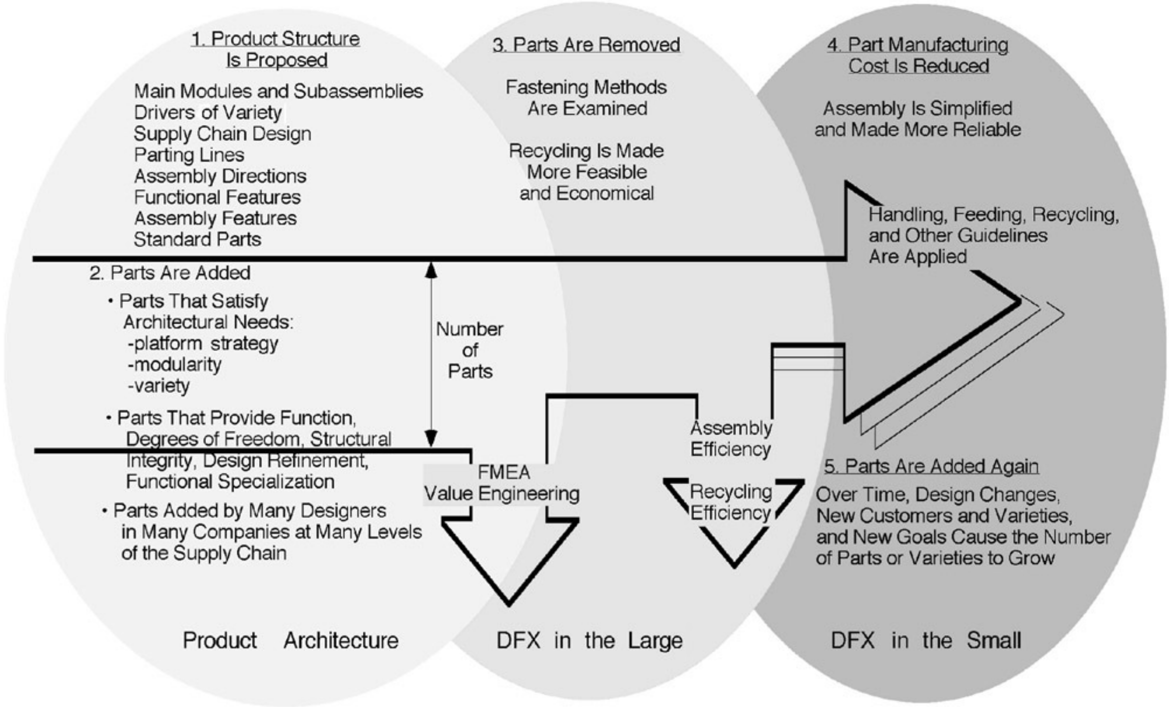

Figure 2.7*. Relationship between Product Architecture, DFX in the Large, and DFX in the Small. Part reduction and design simplicity is desired during the design process. Width of the arrow represents the number of parts in design. [Source Whitney 2004]*

When product architecture is defined, a structure for the product is proposed and parts are added through a variety of mechanisms and for a variety of reasons. Value engineering and DFX in the large tend to reduce the number of parts, while DFX in the small seeks to lower their cost and make their assembly and eventual disassembly more economical. However, as time goes on during the product's life, various forces tend to increase the number of parts or the number of varieties of some of them. [Whitney 2004]

Many similarities and coincidence can be found between Whitney's model and Institute of Product Development's top-down approach. Both methods aim to support holistic design process and emphasise the meaning of early designing phases with slight emphasise differences. Top-down approach aims to far-reaching design consequences and to apply DFMA into the whole product range in all product design levels. Whitney's division into DFX in the small and large can be practical for utilisations of DFX in companies. By this division DFX recommendations and tools can be categorised into the tasks that could be applied by an engineer working alone and to the larger issues that should be considered with the interests of others. Accordingly approaches complement each other.

2.4.2 Requirements for DFMA method

It have been identified in many companies that there is a clear need for supporting method for product design that focuses on manufacturing and assembly issues. But how should such a method be structured and used? Eskilander concludes in his doctoral thesis, that a method should have the following characters: [Eskilander 2001, p.19]

- Be easy to learn, understand and use.
- Contain accepted, non-trivial knowledge within the area it is used.
- Support the users to find the weak areas in the product.
- Be common platform to create a common language for several different professions.
- Support teamwork and to continually educate and support the users.
- Contribute to a structured way of working.
- Provide measurable effects from the development work.

The requirements above are fundamental requirements for any method aimed at product development. Therefore the fulfilment of these requirements should be aimed regardless of which DFX area is considered.

Furthermore, Huang and Mak have categorised DFX tool requirements into functionality and operability requirements in a larger scale. They highlight that the importance of the right balance between functionality and operability is pivotal to the success of developing a DFX tool. A sophisticated DFX tool with comprehensive functionality may be too difficult and time consuming to operate. On the other hand, an over simplistic DFX tool may be easy to use but fail to function effectively. Functionality requirements presented by Huang and Mak: [Huang & Mak 1997]

- Gather and present facts.
- Measure performance.
- Evaluate whether or not a product/process design is good enough.
- Compare design alternatives.
- Highlight strengths and weaknesses of the design.
- Diagnose why an area is strong or weak.
- Provide redesign advice by pointing out directions for improving a design.
- Predict what-if effects and provide analysis.
- Carry out improvements.
- Allow iteration to take place.

Operability requirements presented by Huang and Mak:

- *Training and practice.* Concepts and constructs used should already be familiar to the user or can easily be learnt with little effort.
- *Systematic.* A systematic procedure ensures that all the relevant issues are considered.
- *Data requirement and quantitative.* Product and process data must be easily collected and presented to the analyst or the analysis team to enable further action to take place.
- *Teaches good practice.* The use of the DFX methodology teaches good DFX principles, and actual reliance on the method may eventually diminish with use.

- *Designer effort.* The prime user, i.e. the designer or the design team, should be able to use the DFX tool effectively with little additional time and effort.
- *Management effort.* The management is not a prime user, and thus effective use of the DFX tool should not be totally dependent on management support or expectation.
- *Implementation cost and effort.* It costs and takes efforts to implement a DFX tool in practice. It costs and takes efforts to implement changes identified as the result of effective application of the DFX tool.
- *Rapidly effective.* Effective use of the DFX tool should produce visible and measurable benefits.
- *Stimulates creativity.* Effective use of the DFX tool should encourage innovation and creativity, rather than impose restrictions.

Huang and Mak conclude that, even many well-known successful DFX tools do not perform all functionality and operability requirements. Instead they present that many of the more sophisticated functions are usually handled by the user. As a reason to this they propose that these tasks require intensive knowledge applied specifically to the target product and associated processes, while DFX tools are usually developed in a relatively generic sense. [Huang & Mak 1997]

2.4.3 An ideal DFMA method

Eskilander and Carlsson studied in Sweden in 1998, what would be an ideal DFMA tool if engineering industry had the change to wish for. What should it include and how should it be used? The results from their study suggested following requirements for on an applicable DFMA tool: [Eskilander 2001, p. 70–71]

- Support for cross-functional teams.
- Enable transfer of knowledge.
- Include cost analysis.
- Include quality assurance.
- Include manufacturability and assemblability evaluation.
- Provide design suggestions.
- Prohibit unnecessary design variants.
- Be user friendly.

Almost invariably all DFMA methods emphasise the meaning of teamwork and cross-functionality. Designers are faced with complex tasks and close collaboration between different company functions is essential to success in designing. Eskilander and Carlsson conclude that product development can no longer be considered a single designer's task. Accordingly, a DFMA tool must support the formation of a multi functional product development team. Unfortunately, some companies have the attitude that a single designer can handle the entire DFMA analysis. To avoid this kind of misunderstanding a DFMA tool should clearly demand an aspect that requires the knowledge and expertise from several disciplines.

Besides supporting teamwork practices DFMA tool, should also enable transferring and sharing of design knowledge. A tool should be able to record experience and knowledge from projects concerning how products should or should not be designed. This knowledge can then be transferred to the next project and so similar problems could be avoided on next time. This way same mistakes are not repeated, even if the people working in those product development teams will change.

As expected, ability to create cost predictions during the development of a given product was considered as a strong requirement by companies involved to Eskilander and Carlsson's study. Having the possibility to compare two different solutions for product, in terms of the costs incurred by the company, could bring manufacturing costs to become a deciding factor for design. Furthermore according to Fabricius, the designer's ability to design products that cause low overhead costs might be twice as important, as the ability to design for low labour costs. In order to establish the manufacturability of a proposed product design, it is necessary to perform measures and evaluations in a number of areas to arise cost awareness level of designers. A low cost design solution may be inappropriate, if for instance the associated lead time or quality is unacceptable. [Fabricius 2003, p.12]

DFMA tool should also be able to provide a way to assess and monitor the quality of design. How can it be ensured that a product leaving the product development team to be manufactured is good of quality? How to verify that the product is adjusted to the manufacturing system? In other words, method should provide a way to measure engineer's performance. If DFMA tool can verify that the developed product does meet the requirements from the manufacturing system it can, in a way, guarantee the manufacturability quality of the product.

Nevertheless cost estimation was considered important a need for separate manufacturing and assembly evaluation was discovered. This evaluation can underline the true product complexity for the manufacturing engineers. Accordingly a DFMA tool should give an indication on how complex the product is, from an assembly point of view, in order to render it simpler and consequently requiring a less expensive assembly system.

One important viewpoint arisen in Eskilander and Carlsson's study was that most of the DFMA tools are focused on product evaluation. However, no matter how good an evaluation is, there is always a need to know how to improve the areas where the evaluation indicates poor results. To be applicable and useful DFMA tool should be able to provide design suggestions how to improve design.

It was also discovered that preferably a DFMA tool should have an overall approach and holistic design view. The DFMA tool must not sub-optimize the new products with regards to the rest of the product assortment. Creating solutions that result in extra and unnecessary variants must be avoided. Tool should also support the product development team to consider the rest of the product assortment while developing new products. The application and use of DFMA tool should also be user friendly and avoid the need for extensive education. Software based DFMA tools were also preferred.

2.4.4 DFMA procedures

Boothroyd and Dewhurst's DFMA

The foremost and well known DFMA method is Boothroyd and Dewhurst's DFMA. This method emphasises the meaning of conceptual design, where most far-reaching design decisions are made. According to Boothroyd and Dewhurst the best results in a view point of production would be achieved, when DFM and DFA tools were combined and utilisation was systematically guided. Boothroyd and Dewhurst named this method as a DFMA. Method is cost-oriented and thus product and production optimization is performed in cost reduction perspective. The main steps of the procedure are described on the following figure 2.8.

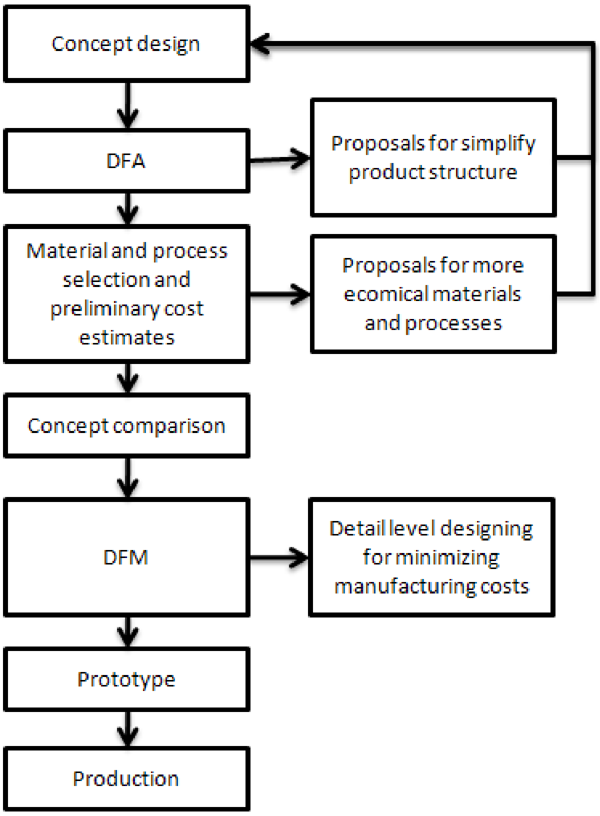

Figure 2.8. *Typical design phases on utilising DFMA techniques on designing. [Modified from Boothroyd et al. 1994, p.11]*

In this procedure DFA and DFM are carried out separately. DFA analysis is carried out first to simplify product structure, which is followed by material and process selection. According to Whitney, the first phase considers all the parts at once and adds assembly process criteria to the search for a good product architecture, while the second phase looks carefully at the surviving parts to see how their fabrication (DFM) and assembly can be improved. [Whitney 2004]

Boothroyd and Dewhurst have presented that, the theoretical minimum number of parts can be determined by ask three following questions of each part in the proposed assembly. Theoretically, only parts satisfying one or more of these questions must be separated. [Ulrich & Eppinger 2008, p.224]

1. Does the part need to move relative to the rest of the assembly?
2. Must the part absolutely be of a different material from the other parts?
3. Does the part have to be separated from assembly for assembly access, replacement, or repair?

Part amount reduction is considered as the most effective way to ease the assemblability, which is natural since if part can be removed a lot of work can be saved. Part reduction has multiple costs save effects, including: designing, prototyping, manufacturing, purchasing, material handling and information management cost savings. In addition according to Boothroyd et al. part-count reduction, leads to simplified designs, provides not just labour and materials cost reduction but has a positive, and pervasive, downstream influence on manufacturing overhead. Part reduction is pursued for example by consolidating parts to be multifunctional. Right material choices and fastening methods also reduces required part amount significantly. The need for separate fastening components, like bolts, nuts and rivets is reduced in the first place.

After assemblability, material and process selection has been conducted for each concept, concepts are compared and evaluated. Best concept is chosen for further development and DFM analysis is carried out on detail. On this phase manufacturability of each part is analysed and evaluated. DFM analysis is conducted to minimize manufacturing costs of each part. Boothroyd and Dewhurst have also developed computer software for DFMA analysis. This DFMA analysis tool is discussed later on.

A seven step DFM procedure

Institute for Product Development from Technical University of Denmark have developed their own *a seven step DFM procedure* to support to design more competitive products. Procedure emphasises especially the meaning of conceptual design. The procedure consists of a number of activities that must be carried out sequentially in order to raise the level of competitiveness. A *seven step DFM procedure* has a broad definition of manufacturing. The DFM abbreviation includes component manufacturing, assembly, logistics and packaging-operations. All operations needed to manufacture a product are then included in term DFM. Hence, the manufacturability of a product is considered as a much more general term than the degree to which the individual components are suitable for the manufacturing process.

A seven step DFM procedure includes the following steps. The goal of the procedure is to find an optimal DFM concept for further on development. [Fabricius 2003, p.20-29]

1. *DFM Diagnosis.* Determination of the manufacturability of present products and comparison to similar products on the market.
2. *Setting DFM objectives.* Setting objectives for the manufacturability of the future DFM product. These objectives should clarify to the design team, what it takes to ensure the competitiveness of the future product. It is emphasised that without consensus and commitment on the DFM objectives, the team members will inevitably work with different objectives for the future product.
3. *Identifying Main Functions.* The product is broken down into main functions to help the team to remove the focus from revising the detailed design of the exiting physical product, to achieving the same functionality in the best possible way.
4. *Clarifying Evaluation Parameters and Design Ideas*. Step four focuses on clarification of evaluation parameters and design ideas for each main function. Within DFM the design ideas are specifically aimed at improving product manufacturability without compromising the product quality. Accordingly evaluation parameters should include both *manufacturability drivers*, which contribute to the improvements of the overall manufacturability of the product and *critical technical requirements*, which support technical requirements in order to maintain the overall product quality. By clarifying these two kinds of evaluation parameters design team can concentrate on DFM ideas that contribute significantly to the overall manufacturability and do not jeopardise product quality.
5. *Conceptual Design.* Based on accumulated DFM ideas the generation of alternative conceptual designs by determining product characteristics in a top-down manner can now begin. It is necessary to create number of different, alternative conceptual designs, in order to allow a comparison of performance. If too few concepts are investigated the finished product might be priced out of the market too soon, by competitors who are more thorough in investigating alternative conceptual designs. It might be also beneficial to try to create a number of ideal concepts before actual concept generation begins to show the extreme solutions. E.g. the direct-cost-ideal, the overhead-cost-ideal, the flexibility-ideal and the lead-time-ideal product concepts. Concept design must be determined in a top-down sequence, to ensure that fundamental product characteristics are decided upon, before design details are specified. The necessity of this sequence can be seen by the fact that any decision on a certain level are appropriate without understanding the preconditions decided on at the higher levels.
6. *Evaluation and Selection.* Assessing the manufacturability of the proposed conceptual designs and comparing them to the DFM objectives. After having made sure the conceptual designs fulfil the DFM objectives, the selection of the overall best conceptual design must be done.
7. *Transition to Design Formation.* Conveying and communicating the chosen conceptual design to the product development tea, which then carry out the detailed design in parallel to the marketing and production development, in order to realise the chosen concept to its full potential. A smooth transition from conceptual design to full development is critical importance. Thus the concept

evaluation and selection must be observed very carefully, to avoid a situation where conceptual decision is questioned again and again, and design teams find themselves running in circles at this stage.

2.4.5 DFMA guidelines

Design guidelines are qualitative descriptions of good design practices. They present the preferable and avoidable practices in product designing. Design guidelines are intended to be used by designer during design synthesis. [Tichem 1997, p.29]

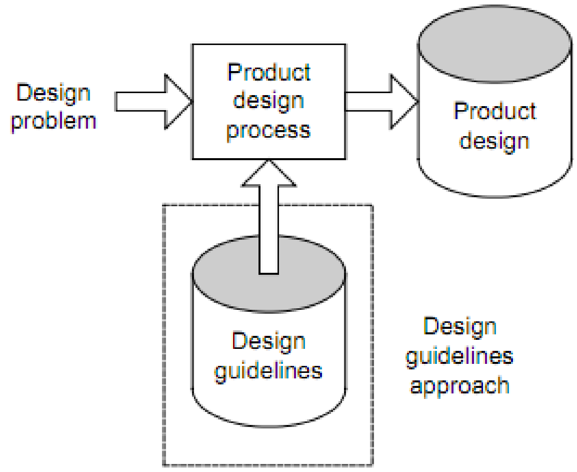

Figure 2.9. *Schematic overview of the design guideline approach. [Source Tichem 1997, p.29]*

Designers have to understand the importance of processibility of a product to be able to design competitive products. Various design guidelines have been developed to aid designers to design more easily manufacturable and assemblable products. One of the best known DFMA guidelines is developed by Professor Henry Stoll [Sage & Rouse 2008, p.527]:

1. Minimize the product's part amount.
2. Design a modular product.
3. Use standard components.
4. Integrate parts, aim to multifunctional components.
5. Design components, which can be used widely on different products.
6. Design easily manufacturable products.
7. Avoid using separate fasteners.
8. Minimize assembly stages and positions.
9. Maximize commonality and compatibility.
10. Minimize handling.

Multiple other DFMA guidelines and principles have also been presented, with a slightly different emphasises. The following guideline combines aspects of theoretical minimum number of parts and Henry Stoll's guidelines and aims to affect higher level product design on early design phases. [Lempiäinen 2003, p. 164; Huhtala et al. 2009, p.233]

1. Aim to clear and simplified design. Minimize the amount of parts needed. Less part handling needed. Reduced assembly time and better productivity achieved.
    a. Minimize the amount of different parts needed. Cost viewpoints, avoid small lot sizes.
    b. Never design an item that can be catalogue bought.
    c. Minimize the amount of tools needed for assembly.
    d. Favour subassemblies especially which can separately tested.
2. Standardize material selection and use standard components as much as possible. Improved inventory management, fewer amount of different tools needed and the benefits of mass production could be better utilised even with small volume.
3. Rationalize product designing. Standardize materials, components and subassemblies by product families in order to improve scale of economies in production and to reduce tool and machine costs.
4. Modular product structure. Adjustment to varying customer requirements can be achieved by late differentiation, after basic products assembly and JIT-production can be streamlined and simplified.
5. Use as wide tolerance area as possible. Avoid unnecessary tolerance and surface demands on components. Production costs are reduced and handling during assembly can ignore vulnerability.
6. Choose materials, which fit to function and to production process. Functionality is not the only criteria. Choice of material must also fit to production process, in order to ensure the products reliability and cost structure.
7. Minimize the need for unproductive operations. Handling, finishing and different kind of inspection operations minimizing reduces costs and the lead time of assembly work.
8. Team work. Support concurrent engineering and take advantage of cross-functional teams on designing projects.

More precise and detail guidelines have been developed to support manufacturability and assembly considerations. Product's part amount is the main factor to define product's assembly time. However various other aspects have an effect too, like part handling, aligning, accessibility and fastening. For these reasons it is logical that too different assemblies, which have identical amount of parts may have totally divergent assembly times. Parts geometry and assembly position have a significant impact on this. According to Boothroyd and Dewhurst the ideal characteristics of a part assembly are: [Ulrich & Eppinger 2008, p.225]

1. Part is inserted from the top of the assembly. Gravity helps to stabilize the partial assembly and assembly worker can generally see the assembly location.
2. Part is self aligning. Parts and assembly sites can be designed to be self-aligning so that fine motor control is not required of the worker. The chamfer is the most common self alignment feature.

3. Part does not need to be oriented.
4. Part requires only one hand on for assembly.
5. Part requires no tools.
6. Part is assembled in a one single, linear motion.
7. Part is secured immediately upon insertion.

Besides design guidelines different types of checklists are common way to support designing task and to make sure that all beforehand known design aspects have been considered. Checklists can be created, copied and easily modified to fit various different purposes. Checklists can be utilised on different design levels and can be tailored to fit for specific products, product families or components. Checklists are typically conducted in form of questionnaire, which include questions regarding various DFMA aspects and preferable answers to those questions. The main idea behind questions is that this would ensure and remind designers to take into consider various design aspects and consequences.

The utilisation of checklists should be as easy as possible, because the primary aim is to encourage as wide adaptation as possible. Thus the structure and amount of questions should be carefully considered. Checklist should not be strenuous or too heavy to use. The main point is to be quick and flexible way to ensure quality of design. Furthermore, checklists may also be extended to a company's quality system. This will leave post to designing documents and enables afterwards traceability of how well DFMA considerations have taken account and what are the reasons for a possible deviation from the planned. [Lempiäinen 2003, p.154]

Assembly access

- ☐ Assembly access has been examined (with all possible option)
- ☐ No reorientation of the whole assembly required to get access for installation
- ☐ No blind assemblies. Assembly can be seen and guided by operator.

Part insertion

- ☐ Working postures and part insertion directions has been considered (A simple downward insertion motion is the best)
- ☐ No excess insertion force needed
- ☐ Part features used to facilitate alignment and insertion (E.g. chamfers, tagers, etc.)

Joining and fastening

- ☐ Minimal effort required. Common fasteners and converge bolt sizes used.
- ☐ Tool clearance has been ensured. (E.g. larger clearance requirements for torque wrench, torque gun, extension bar etc. has been considered)
- ☐ All necessary screw/bolt torques are documented

Special tools

- ☐ No need for special tools or at least it should be planned with production well before prototyping

Figure 2.10. *An example checklist to ensure manual assembly considerations. Checklists are used to ensure that various design aspects have been considered on designing.*

However, checklists also have their weaknesses. It is usual that disciplines like DFMA rely on checklists when they are being learned, but designers quickly abandon checklists once they get the gist of it. The typical explanation for this is that the designer now fully understands the discipline and keeps it on mind all the time. However, without a formal and methodical way of tracking a product through the concept, design and manufacturing stages DFMA can lose its power and become little more than a check in the box mentality. For these reason checklists should be as user friendly as possible to ensure regular utilisation.

2.4.6 Advantages and disadvantages of design rules

Previously presented generic design guidelines are valuable tools for many manufacturing companies to aim focus on right issues and development areas in designing. However, the usefulness of design guidelines has been also questioned, mainly because of the wide generalizations and faced usability challenges. Compliance with the rules can be a very challenging task. Egan argues that the use of design rules, as the ones earlier presented, are disadvantageous, because of three reasons: [Eskilander 2001, p. 72]

- *Applicability vs. usability.* Simple rules are often too general for any given problem and therefore not accepted or used. The number of rules is also problematic, because the more rules exists the more problematic it becomes to select applicable rule to use and how to prioritise with rules.
- *No procedure for use.* Although the rules contain useful knowledge, the lack of procedure for how to use them in a structured manner reduces the usability considerably.
- *No qualitative design evaluation.* Design rules only provide unstructured qualitative advice. However, in order to evaluate designs there is a need for a qualitative method.

For example, earlier presented Boothroyd and Dewhurst's design rule to determine theoretical minimum part amount is very rough and unsophisticated way to study the need for the parts. Theory does not take into account that reducing the number of parts will also cause some additional costs. Moreover design rule provides no way to evaluate the overall effects achieved by part consolidation. As a drawback, part reduction and consolidation may easily result more complex and expensive design. In addition, it have been criticised that in many cases efficient utilisation of DFMA guidelines requires rather large batch sizes. [Pulkkinen & Riitahuhta 2002, p.36]

The main advantage of design rules is that they are usually relatively easy to understand. However this can also be a drawback, since the design rules may be over simplified for solving a specific design problem. Tichem further points out the following drawbacks in the use of design rules: [Tichem 1997, p.29]

- The application of a specific design rule is left to the judgement of the designer. There is no mechanism, which trigger the designer to select a certain design rule.

- There is no support in deciding when to implement a design rule or when to reject it.
- The translation of the design rule into information regarding the actual design is also left to the designer.
- Design rules seldom contain a quantification of the effects reached in applying a design rule.

Moreover, it have been criticises, that the level of knowledge required to utilise DFMA method efficiently can be very deficient and limited in early design phases. This is natural, since information lack is highest on early design phases and thus evaluation between different design alternatives may feel uncomfortable and doubtful. [Egan 1997]

Whitney discusses about the role of product character to DFMA guidelines. He explains that it is likely that consumer and industrial products will provide different opportunities for DFMA. He explains that consumer products like food mixers and can openers are subject to much less stringent performance and durability requirements than are industrial components like automobile transmissions and aircraft engines. As an example he presents that home handyman's electric drill will get as much use in a year as a professional carpenter's drill will get in a single day. For such reasons, designers will choose materials, part boundaries, and fasteners much more carefully for an industrial product. The result is that opportunities for part consolidation and elimination of fasteners will be fewer for industrial products. Whitney also explains that some attempts to reduce the number of fasteners in major machinery joints in the name of DFA have been known to cause catastrophic failure. Therefore the product characteristics set restrictions for the applicability of the design guidelines. [Whitney 2004]

2.4.7 DFMA analysis

Quantitative analysis has been commonly adopted to evaluate design work's outcome. In this analysis the product can be divided into subassemblies, whose assemblability is separately analysed and evaluated. By these mean, analysis is conducted separately for every assembly stage. Numerical values are given for each sub-assembly and whole product's assemblability scores are summed up. Quantitative analysis makes it possible to compare and monitor products' manufacturability and assemblability concerns and progress.

Analysis can be conducted for products that are already in production, or based on design documents and drawing or in the conceptual design phase, when a large part of detail design still lacks and is only in the mind of designers. The best advantage of DFMA analysis is achieved, if the analysis can be conducted during product's design phase, before actual product is even released into the production. In this way DFMA analysis enables comparison of different design solutions earlier in design process and makes it possible to avoid unnecessary iteration back to the designer's table. The benefit sought by DFMA analysis is to look at a design before it's released to manufacturing and get rid of a lot of waste. It enables to acquire more specific information of product and sub-assemblies to whom may require it. A prerequisite for the analysis is that the design has to exist in some form. Accordingly it is logical that the accuracy of analysis improves, as design becomes more specific. Often, moderate precision information is acquired after conceptual designing to be utilised to create cost estimates, production planning and material allocation. [Siuko 1991, p.8–10]

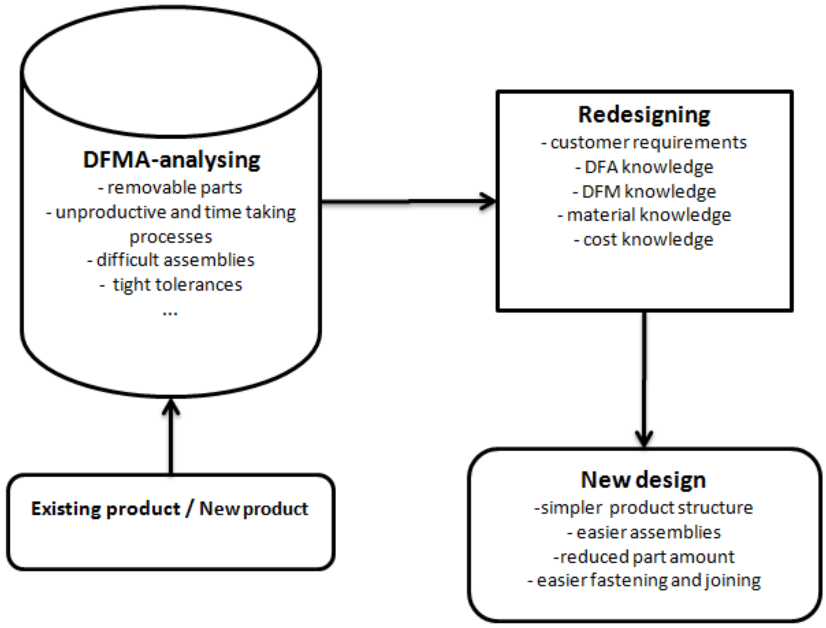

Figure 2.11. *Schematic overview of DFMA analysis. Analyse brings manufacturability and assemblability issues transparent and shows improvement targets.*

Many of DFMA analyse methods rely on databases, which have been collected by research and experience concerning assemblability and manufacturability information. Methods are used to calculate estimates of the easiness of product's manufacturability and assemblability based on database information. Some best known methods are: [Leaney & Wittenberg 1992]

- The DFMA method exploited by Boothroyd Dewhurst Inc, USA
- The Lucas Design for Assembly Methodology, DFmA, by Lucas-Hull, UK
- The Hitachi Assemblability Evaluation Method, AEM, by Hitachi Ltd, Japan

Boothroyd and Dewhurst have developed software for DFMA analyses. This software can compute quantitative measures how well suited a given product or its components are to assembly and manufacture. Method calculates estimated assembly time based on given product structure and part features. Assembly time is used, because it is clear and easily understandable measure to evaluate the easies of assembly. In addition, assembly time can be further used to estimate assembly operation work costs and profitability of needed machine and tool investments. Software covers both DFA and DFM analysis and it can be utilised for both automatic and manual assembly work. Software's aim is not to calculate exact assembly times or costs, but make it possible to compare different design concepts and recognize critical improvement objects. Boothroyd and Dewhurst have documented significant reductions in parts count (51%)

and cost (37%), time to market (50% faster), assembly time (62%), and manufacturing cycle time (57%) as well as improved quality and reliability (68%) by systems users. [Boothroyd Dewhurst Inc. 2011]

Lucas Engineering and Systems Ltd. has developed and named another well known DfmA-method. The Lucas DfmA is a generic design model linking Quality Function Deployment, QFD, with a right timely use of DFA in different development phases. The main difference between Boothroyd and Dewhurst DFMA and Lucas DfmA, is that the foremost uses assembly times and the latter uses a point scale to measure relative difficulty of assemblability. DfmA method is divided into four steps in order to indicate a direction for further design work: analysis of functionality, manufacturability analysis, component handling analysis and fitting analysis. First, design efficiency is calculated on the basis of an *analysis of the functionality* of the components comprising the product. This efficiency index, expresses the ability of the team to design the product with as few components as possible so that the functionality of the product is still maintained. Secondly, *manufacturability analysis* is conducted. The consequences of the design decisions on the technological and economic feasibility of the component manufacturing are assessed. Thirdly, the relative cost of handling each component is assessed and a target cost for *component handling* is set. The last phase is *a fitting analysis*, which is performed to determine the cost of the assembly of each component. These analyse results are used to allocate redesign resources to the most critical targets in order to reduce costs and to improve measured performance ratios. That why, the DFmA is predominately concerned with direct manufacturing and environmental issues. [Fabricius 2003, p.17–18]

Hitachi Assembly Evaluation Method is based on two main criteria. Method calculates a numerical value to asses design quality or the difficulty of assembly operation, which yields an evaluation score E. Another evaluation criterion is an estimated assembly cost ratio, K, which is used to estimate assembly cost improvements. Assemblability evaluation is conducted by reviewing assembly stages, which have been divided into part insertion phase and part fastening phase. Method assumes that, these both phases are done for each component and these phases are evaluated. Penalty points are given and defined in order to Hitachi assemblability information database. According to AEM a simple downward motion is considered to be the fastest and easiest assembly operation for a human or machine to perform. Penalty points are therefore assigned to every motion or operation that differs from this. Penalty points are calculated in a similar way for each component of a product. The E-score for the whole product is calculated as an average of all components. E-score doesn't, provide feedback on the advantages to be gained by reducing the number of parts in the assembly. K-score is used for this purpose. K-score can be understood as an assembly cost ratio between previous and new design. It can be calculated by dividing new design's assembly costs by old design's assembly costs. Assembly costs are defined by historical data and by estimating assembly task's duration and standard costs. Designer's target is set to achieve K-score smaller than 0,7. This can be achieved by reducing the number of parts in the redesigned assembly and making assembly operations easier. The Hitachi Assembly Evaluation Method will help the designer focus on problem areas in the design, by setting targets and making him endeavour to achieve target values of E and K. [Leaney & Wittenberg 1992]

All described DFMA evaluation techniques are available in a form of software package. Computerized assemblability evaluation makes it possible to asses assemblability aspects based on 3D-models. Virtual assemblability assessment can thus be conducted on earlier design phases, without physical parts or prototypes. This work procedure makes it easier to compare alternative design solutions and make design changes without considerable additional costs. Moreover DFMA software enables to instruct the user to apply engineering guidelines and to support design decisions. Documentation of analysis is also threatened since software can provide standard reports. As a drawback virtual analyse doesn't directly deal with real parts, and thus may not provide as informative data as real prototype assembly. Prototype assembly makes it possible to inquire assembly workers opinions and viewpoints. [Leaney & Wittenberg, 1992] Whitney also point out that too strong reliance on the score can lead to incorrect design decisions. Moreover blind utilisations of a score-based system can lead people to think that experience is not needed to get good results. [Whitney 2004]

In addition, one drawback in quantitative evaluation is that the results have to be interpreted in requirements for redesigning the product. However, there is usually no clear advice to the user for how to redesign a product with a low score. In a qualitative evaluation the evaluation criterion itself is an example of a way to improve the product if the best score is not fulfilled. Eskilander criticises in his doctoral thesis, that simply using the evaluation criteria as design rules is not enough. He emphasises that to be useful, the design rules need to be more specific that evaluation criterion. In most methods, the use of design rules to inform the user of the method how to design is missing. As a conclusion he points out that there is a need for a method that uses qualitative evaluation in combination with the design rules that are general for any assembly process. [Eskilander 2001, p. 56]

In summary, all DFMA evaluation techniques described here are very detail level analyse tools and efficient utilization requires wide knowledge from various engineering areas. Carefully performed analyse requires considerable amount of time and design recourses. That is why the best results with these tools could be achieved with volume products. The size of an assembly is another important limiting factor. Typically these tools could be most successfully utilised with mechanism-based assemblies of a size that could be assembled on a desk top. Typically they would be mobile phones, video recorders, computers or high volume car sub-assemblies like water pumps and pedal boxes. The methods are not meant for large products of the size of a complete car or working machine. For such large products the size and weight of component parts and the need for the assembly worker to walk about means that the DFMA synthetic data is not applicable. Other detected problem area for detail level DFMA analysis is products including wiring and wire harnesses. DFMA evaluation techniques are seen to provide and disciplined way of raising the importance of assembling in the mind of the designer. DFMA evaluation techniques can be seen to play important role in facilitating simultaneous engineering. [Leaney & Wittenberg 1992]

2.4.8 Why DFMA is not more widely used?

Carlsson conducted a study in Swedish industry in 1996, why DFMA methods are not more widely used. He reported following three major reasons, why DFMA is not used more: [Eskilander 2001, p.32]

- *Poor knowledge of the methods.* The most obvious reason is that the methods are poorly known. In a few companies, there is a small specialist group that knows of the methods are available, but production engineers and designers have little knowledge about the methods.
- *Management priorities.* Many companies had prioritised product performance higher than low manufacturing costs. Thereby no great pressure from the management to lower manufacturing costs comprehensively existed.
- *Work overload.* Engineers felt that their workload is so high that they felt they do not have time to work with another method. According to Fabricius, it is very common that daily activities seem to demand more attention than development projects. Continuous fire fighting is given higher priority than prevention of production problems. [Fabricius 2003, p.46–47]

Furthermore, the lack of economic proof of why companies should start to work with DFMA was discovered as a one barrier. No reliable way exists to show how much money a specific company could save if working with DFMA. It all depends a lot on how good the product design is today and how well a DFMA method can be implanted. There are a lot of case studies showing significant savings, but there is no way of guaranteeing a certain amount of savings for a specific company. [Eskilander 2001, p.33]

In addition DFMA utilisation requires a long term commitment. The results of product development and utilisation of DFMA method are not easily measured and they are realized during the production of designed product long after the design process has been finished. [Saarenrinne 2009, p.51]

2.5 Implementation of DFMA method

DFMA rules, guidelines and analysis tools could be solely used as designers' tools to help consideration of manufacturability and assemblability in designing. This requires that common design guidelines are documented, shared and designers are educated to utilise DFMA tools. However, in this case DFMA potential is not fully exploited. To be able to design optimal products in the company's point of view, DFMA should be integrated to company's product development process to support cross-functional collaboration. This way DFMA highlights that manufacturing problems are not only matters of production department, but a common problems, that all functions should be involved to solve. [Fabricius 2003]

A reconciliation of DFMA method, cross functional cooperation and integration to product development process is a major project and management's commitment is essential. Siunko presents in his master of thesis that, even the initiative to implement DFMA method may become from any function of the organization, the implementation decision have to be made at high enough organizational level. This is required to make sure that all functions are fully involved and committed to the utilisation of DFMA. Management's full support is also essential to make sure that enough resources are available to the development of eligible DFMA system in a long-term. That is why the informing of the DFMA should to be started from the management. [Siuko 1991, p.38]

According to Eskilander there is probably no right way for all companies to implement DFMA. Therefore, the initial use of DFMA should be opportunity driven. Finding the first successful demonstrator of DFMA project can be helpful to find further opportunities to be pursued until the DFMA tools and techniques become a normal process for product designing. [Eskilander 2001, p.30]

2.5.1 Decision needed to utilize DFMA

To be enable efficient implementation of DFMA management's approval is essential, after that the actual preparation work for implementation can be started. Necessary decisions to create on operational DFMA system are shortly introduced next. Following main issues have to be solved and considered on the creation of DFMA system: [Siuko 1991, p.38–41]

- Decision to utilise and integrate DFMA into product development process and to include manufacturing and assembly considerations and evaluation criteria into design reviews. How to promote and show that the DFMA method would be greatly beneficial to the business? How to commit all parties into DFMA?
- Decision and careful selection of the pilot DFMA project. DFMA method cannot be fully implemented once in company's all product development projects. It should be implemented in small steps to make it more manageable. The right selection of the first project is particularly important. It should neither be too ambitious nor too modest. The DFMA objectives for the pilot project have to be commonly and clearly agreed. Without consensus and commitment to the DFMA objectives, the team members will inevitably work with different objectives for the future product.
- Decision to develop departmental cooperation. DFMA aims to minimize total manufacturing costs and thus designers need expert knowledge from various engineering areas to be able to consider total cost effects. How to organize cooperation and to enable cross functional team work in organization? Are all parties ready to change their working methods and able to adapt to work in cross functional teams? Persons responsible to develop cooperation practices between departments have to be appointed.

- Decision of how to create a working feedback system to collect information towards made design decisions. Both internal and external collection of feedback has to be ensured. In the core of DFMA is continuous feedback linkage between designing and production functions. It should be carefully considered how this feedback collection should be arranged. Too many times, feedback collection from the manufacturability and assemblability experts, production employees themselves, is failed or is not effectively arranged. Many companies have initiative systems to collect development ideas for further development. However, in many cases it possible that many development ideas are considered to be so rough, that actual initiatives are never posted. For these kinds of reasons more personal relationships between designers and production personnel should be strived. Customers' feedback collection is usually handled by marketing department. However, it should be confirmed that the feedback is not only transmitted to designing department in form of customer claims. Positive feedback is also valuable for designer to gain on understanding of preferable design solutions.
- Decision of how to maintain and develop DFMA system. Proper organization should be built to maintain and update the DFMA system in sync with changes in circumstances. Process owner have to be appointed. Appropriate measures of performance have to be introduced to provide control over product design activities in terms of quality, cost and delivery.
- Decision to acquire and introduce DFMA analysis tool. Review of which kind of analysis tool, would be most appropriate for the company circumstances. Review of analysis tools should be conducted in liaison between design and production department representatives.

2.5.2 DFMA training

Personnel education and motivation have a major impact on how DFMA can be exploited in companies. Motivation may be needed to show the benefits that could be achieved with DFMA and to tackle the possible change resistance, caused by the fear of increasing work load. DFMA implementation and closer teamwork approach have the greatest impact to designers' job. New way of working may first feel more complex than earlier and thus it should be ensured that tangible results are achieved as soon as possible. Preferably tangible results should be achieved immediately from the first development project. Designers carefully training and education of the DFMA methods and advantages seek by are therefore extremely important. Designers whose have understood the meaning of manufacturability and assemblability are able and willing to widely utilise opportunities provided by DFMA. When the method and the way of working are properly learnt and mastered, less iteration work is needed in designing and consequently the whole product design can be conducted more efficiently. [Siuko 1991, p.43]

DFMA training should strive to identify problem areas and enable to compare the manufacturing and assembly consequences between alternative designs. Good and poor examples of own products and assemblies should be collected and presented as a part of the education. One of the most efficient ways to illustrate and underline the meaning of DFMA viewpoints is learn by doing. As a part of the training, designers should try to perform assembly work personally, in order to acquire firsthand knowledge. [Siuko 1991, p.42]

The study of the manufacturing performance of competing products could also been utilised as a rich source of innovation and to motivate attendees towards DFMA. The information received by competitors benchmarking will also serve as a reference for the objectives in order to ensure a sufficient competitiveness of future product. Without commonly agreed and committed on DFMA objectives, the team members will inevitably work with different objectives for the future product. [Fabricius 2003, p.22]

Product's cost structures could also be inspected more detail as a part of the DFMA training. Cost structures can provide very valuable information for designers to understand how costs are committed and incurred along products' entire life cycle. According to the Institute of Product Development, the ability to design product with a moderate overhead costs is often overlooked by management in many companies. All in all, overhead costs are troublesome to manage, mainly because of unclear cause-effect-relationship. Often it is not obvious, that overhead costs to a high degree are caused by the early design decisions during the conceptual design phase. Because of the delay between cost commitment and cost-incurrence, problems with overhead costs in designing emerge much later as an efficiency problem in many other departments. Fabricius illustrates this by an example of designer who chose two different screws instead of two identical ones. By this way designer has immediately caused an increased work load in both purchase and logistic departments. [Fabricius 2003, p.12]

Production personnel should also be trained and informed of DFMA. By training basic DFMA principles, production employees became more active and cautious to notice numerous development possibilities. Furthermore, feedback should not only focus on change requests. Production should also be encouraged to give a positive feedback from good design solutions. This enables designers to become more aware of production preferences. [Siuko 1991, p.43]

The better the benefits and advantages sought by DFMA can shown and demonstrated, the easier it will be to start to use it. The aspects of user friendliness must not be forgotten in DFMA implementation.

2.5.3 Challenges DFMA project may encounter

The need and problems that DFMA deals with are usually well recognised in companies. DFMA can even be perceived as an obvious concept and a solution for designing problems. However, it is not uncommon that companies may encounter serious problems when trying to implement DFMA.

Prerequisite for successful DFMA project is expertise knowledge from various engineering areas. Cross-functional teams are commonly utilised and needed in DFMA projects. Suspicious towards interdisciplinary team work associated with DFMA may thus set severe challenges for DFMA project. The roots of this matter are natural, since people tend to resist with all kind of development projects, in the fear of increased work-load. New way of working may be felt somehow threatening, compared with working in the safety of departmental fortifications. [Fabricius 2003, p.43]

It is probable that DFMA project may encounter some resistance from engineering department side, because that is the function which working procedures are evaluated and challenged most with DFMA. The old design team may be reluctant to accept that their design can be actually improved. The design team may also be unwillingness to be subjected to systematic procedures and work methodology. This may be especially problem, if designers are used to have free hands and no restrictions on designing. Old habits and work patterns may thus set some obstacles for DFMA implementation. Designers may feel that their work is such unique and complex that it cannot be guided. Designers may also be reluctant or not used to work with absolute project objectives characterised by DFMA. This kind of change resistant might be expected, since absolute project objectives makes failure apparent to the management. [Fabricius 2003, p.43]

According to various references an important prerequisite for DFMA project is top management's commitment. Top management's commitment is essential to ensure that DFMA project could be successfully conducted in a full scale. Another first priority issue is that DFMA is started with carefully selected pilot project. Pilot project should be carefully selected to ensure that conditions for success are realistic and possible. Local success story is desired to show what kind of results could be achieved with DFMA and to support wider implementation. Successfully conducted pilot project also weakens the possible scepticism towards the method. Pilot project selection must be done carefully, since a failure in this might upset the implementation of DFMA for years and ruin the possibilities for further implementation. Ideally the pilot project should be important and the object of the project should be a typical product. Moreover, the need for an improved design should be apparent to all people involved. [Fabricius 2003, p.43]

However, it is natural that DFMA implementation may encounter some drawbacks. If DFMA project is conducted in an unfortunate way, the achieved results may be less favourable than expected. According to Ulrich and Eppinger these main drawbacks relates to time and cost considerations. The design project may take a longer time than expected, when DFMA tools and activities are included. Especially design teams that are not used to working with DFMA may experience a longer design time. Extended design time to get familiar with DFMA should be considered in a planning and scheduling of the first DFMA projects. Nevertheless, it is possible that the time to market may be delayed if DFMA is used an unfortunate way. For instance, too ambitious and unrealistic DFMA objectives and requirements may lead to this. The product may have to be re-designed more than planned to meet set requirements and time to market may be delayed. Unfortunate DFMA utilisation may also lead to increased product costs. Product cost may be increased if parts are integrated in a poor way and the reduced overall part amount is achieved at the expanse of more complex parts. The manufacturing cost of a complex part may be higher than the costs for example three simple parts that require assembly. In addition, DFMA's unfortunate implementation may result requirements for more complex and expensive manufacturing processes and tools. [Ulrich & Eppinger 2008, p.228–229]

Most of these potential drawbacks could be avoided if DFMA is not used by designers alone, but in design teams including for example production engineers, production personnel, quality engineers and cost controllers etc. [Eskilander 2001, p.33]. The meaning of management's attitude towards manufacturing issues cannot be undervalued. Many problems in companies may inherit if designing team doesn't care about production problems, because company's management considers incorrectly that production department is responsible for all manufacturing related problems. That's why company's management should have a clear overall picture and emphasise that manufacturability and assemblability are created on product development. Management have to understand that DFMA focuses to prevent manufacturing problems not to fix them. [Siuko 1991, p.38]

3 COMPANY PRESENTATION

This chapter described Sandvik Group’s main business areas and concentrates more in Underground Mining -customer segment’s operations. First, short corporate introduction is given. Second, main products and production sites of Sandvik Underground Mining are described. Third, Sandvik’s Offering and Product Development Process is presented and discussed.

3.1 Sandvik group

Sandvik Ab is a high-technology engineering group, with advanced products and world-leading positions in selected niches. Since its founding in Sandviken in Sweden in 1862, Sandvik has developed into a global enterprise, with a wide expertise in the field of materials technology. The Sandvik group operates in three different business areas: Tooling Mining and Construction and Materials Technology. The Group has 47,000 employees, representation in 130 countries, with annual sales of approximately SEK 83 billion during the year 2010. [Sandvik 2011]

The main business offer wide variety of tools and accessories for a need of rock excavation, surface drilling, tunnelling, rock drilling, raise boring and coal and mineral cutting. The Tooling business area focuses mainly on tools and tooling systems for metalworking applications. Major customers include companies in the automotive and aerospace industries. Mining and Construction specializes in rock-working equipment and tools used in mining and civil engineering worldwide. Materials Technology develops mainly products in stainless steel, special alloys and resistance heating materials as well as process systems. Approximately two thirds of the products are industrial-consumption products and one third consists of investment goods. The Group’s goal is to actively contribute to improving the customers’ productivity and, consequently, their profitability. The products and services offered by Sandvik shall provide maximum value to customers in terms of performance, quality, speed, safety, flexibility and economy. [Sandvik 2011]

Sandvik has grown strongly and approximately 7% annual growth has been achieved over the past 20 years. About half of this has come through acquisitions. For instance in the most recent 10-year period, Sandvik has acquired some 50 companies. Strong growth and acquisitions have led to very wide product range. [Sandvik 2011]

3.2 Sandvik Mining and Construction

One of the three main business areas, Mining and Construction is further divided into three customer segments: Underground Mining, Surface Mining and Construction. The surface segment's products are mainly used in civil engineering while underground segment's products are used in mining and tunnelling business.

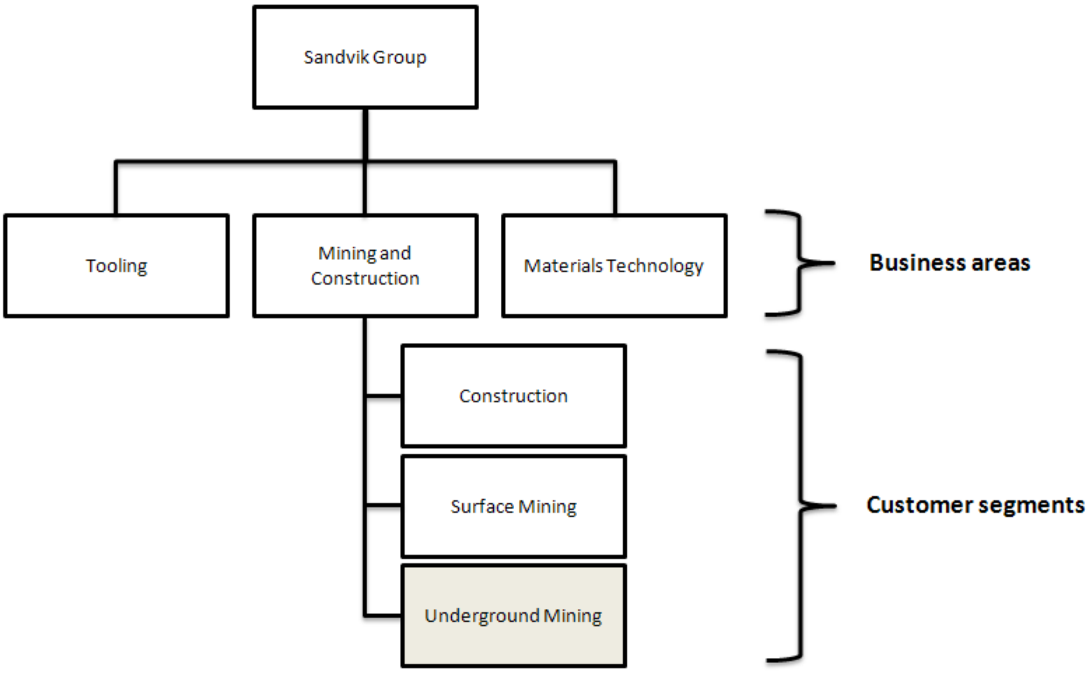

Figure 3.1. *Corporate structure of Sandvik Group in 2011. [Sandvik 2011]*

Research and development activities are integrated in the production organizations, thus every production organization has its own R&D department at Sandvik. The issues with the highest priority in Sandvik Mining and Construction's R&D efforts relate to safety of products and services for the aftermarket. The largest development units can be found in Finland, Sweden, Austria and United States. This master thesis was done in cooperation with the following main production organizations of Underground Mining: Tampere (Finland) underground drills, Turku (Finland) underground loading and hauling and Zeltweg (Austria) mechanical cutting. On these sites production and product development is integrated and physically placed to a same location as production.

The offered product range is highly customized based on customer requirements. The ultimate goal is every time try to satisfy and serve customer needs as well as possible and thus products are largely engineered to order. Hence, especially large portion of drill rigs and mechanical cutting machines are largely customized to individual customer specifications. Therefore manufacturing planning and controlling system needs to encompass preproduction engineering activities as well as manufacturing and supplier operations. In this make-to-order based production system, the customer order represents the unit of control in the master production schedule and the backlog of customer orders forms part of the overall lead time for the product. Overall, order backlog is critical measure for estimating material and capacity requirements. [Vollman et al. 2005, p.449]

Generally mining business is pretty volatile and cyclical according to global mineral prices. Thus, with good times demand and the order backlog can grow strongly and delivery capacity may become a constraint. For these reasons smoother manufacturing and assembly operations were wanted. Briefly, shorter time-to-market and production lead-time were pursued to enable quicker response to the varying market demand. Next, main products and production sites of Tampere, Turku and Zeltweg are described.

3.2.1 Underground drilling and bolting, Tampere

The factory of Tampere consists of three different production facilities and both underground and surface segment's products are produced. Tampere factory employed about 1000 employees in the year 2009. At the movement, product range consists of large amount of different kind of drilling machines which are mainly used in blasthole creation for mining, tunnelling and construction purposes. Following product series are produced: mining jumbos (DD-series), tunnelling jumbos (DT-series), rock support drill rigs (DS-series) and production drill rigs (DL-series). Products are used in very though condition and that is why the most important features of these machines are reliability, safety and robust design to ensure continuous productivity. Products vary a lot, according to customer requirements and varying working conditions. Customers are advised to buy the best fitting drill for their needs and thus every drilling rig is tailored to meet special customer needs. The most important factors are the rock quality, mine's electricity, water and ventilation -systems and operators drilling process. Drill rig can be modified in many ways according to these and many other requirements. Wide range of options is available to finetune the drilling process and to satisfy varying customer requirements in a best possible way.

Currently, the drill rig production differentiates between different models in Tampere factory. The most assembly work is done in sequence and in one assembly station. The extensive amount of work on final assembly makes it difficult to reduce the lead-time. However, large scale production development projects are underway and many improvements have a made for both product designing and to production system. The aim is to favour modular architecture in drill rigs, to enable better fit for line assembly, smoother material flows and reduce the final assembly work by supporting module and sub assemblies. Tampere production site specialised on machine's assembly operations and most manufacturing operations have been outsourced. However, some core components manufacturing have been kept in-house, including rock drills' parts fabrication.

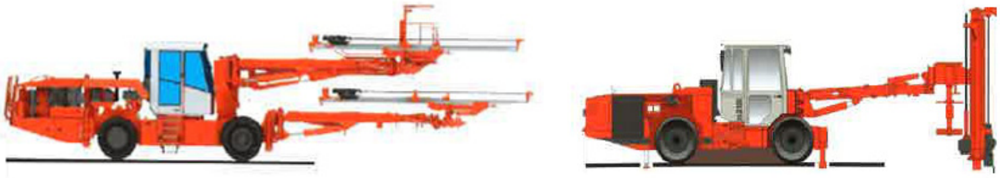

Figure 3.2. On the left tunneling jumbo (DT-series) and on the right rock support drill rig (DS-series).

3.2.2 Underground loading and hauling, Turku

Turku production site is specialised for underground loaders, *Load Haul Dump, LHD,* -vehicles. Underground loaders are used in mines to loading and hauling operations. LHDs are extremely rugged and highly manoeuvrable. High productivity with low cost per loaded ton is pursued. Tramming capacity of loaders vary from 1 to 25 metric tons. Both diesel and electric driven LHD versions are available. Electric LHD provides working environment with zero underground emissions, less vibration, and noise.

In the point of view production, underground loaders differentiate generally from the drill rigs with their relatively simpler product structure. LHDs are also customized to meet special customer needs, but the variety of available option is smaller. Consequently there is less variation in product structures of underground loaders, which advantageous in point of view of the assembly. A lot of progress has been done to develop and facilitate line assembly production of underground loaders. Currently, most common LHD-models are manufactures on line assembly. In addition to assembly operations Turku production site is also specialised on manufacturing operations. Site has its own welding and machining facilities. For example LHDs frames and bucket are manufactured in-house.

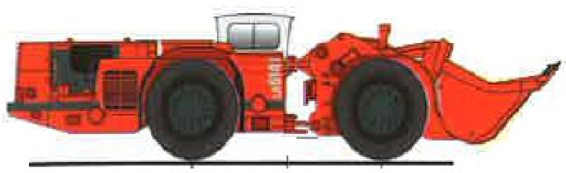

Figure 3.3. *LH514 loading and hauling vehicle, LHD.*

3.2.3 Mechanical cutting, Zeltweg

Zeltweg's production site in Austria has a wide product range. Product range consists mainly from different types of continuous miners. Track-mounted continuous mining machines are extremely powerful rock-cutting machines designed to excavate roadways, tunnels and chambers continuously without using explosives and thus eliminating the need for drill-and-blast. These machines are equipped with powerful transverse cutter heads to proven a cutting performance in a wide range of rock formations. Roadheaders are really heavy machines; heaviest model weights up to 150 tons. Zeltweg's site takes advantage of in-house control over both the machines and their cutting tools. Core components manufacturing have been kept in-house, including gearboxes and cutting heads. A lot of research and development work of core components is conducted in the immediate vicinity. For example gearboxes of roadheaders have to be able to transmit very large forces. Thus all gearboxes are separate tested before assembly and high tolerance requirements have to be achieved in manufacturing. At the moment roadheaders are assembled as a station assembly. This is a consequence of relatively small volume of certain type machines and the fact that products are highly customized according customer requirements. Engineers have roughly estimated that about one fourth of the machine is engineered to order.

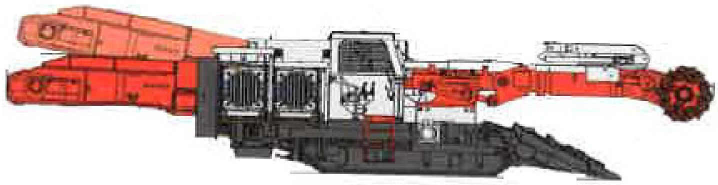

Figure 3.4. *MR340 roadheader.*

4 PRACTICAL PART

This chapter focuses on the practical part of the thesis work. First, the background and the current situation at Sandvik Underground Mining is presented in a viewpoint of DFMA. Second, design department's organization and responsibilities are introduced and the demand for DFMA is discussed. Third, detected DFMA related development issues and areas are discussed. Forth, created DFMA rules and guidelines are discussed and the content is introduced with examples. Fifth, a proposal DFMA system to manage and integrate DFMA into the company operations is introduced and discussed.

4.1 Background and the current situation

At the beginning of thesis work the situation at Sandvik Underground Mining was the following:

- Varying collection of production site specific and common technical standards and specifications existed to aid designing.
- Variable design rules and guidelines were sub-optimized for product lines and locally managed.
- Production feedback and requirements were locally collected and handled. Feedback was mainly collected via PDM system at a form of engineering change requests.
- Generic design processes were documented, but not always strictly followed. Processes were applied in the most appropriate way in according to design projects.
- It was well known fact that products could be more manufacturing and assembly friendly and collaboration practices could be improved globally.
- No common practice existed to utilise DFMA.
- Large production development projects were on the way, focusing on the lean manufacturing.
- Remarkable new product development project were forthcoming.

The roots of the varying design practices laid on the history of the company. Company has expanded by acquisitions and thus different products and organizations have been joined together under the same brand. The company has expanded strongly in recent years, due to the mergers and acquisitions, approximately 7% annually. Offered product range has grown wide and versatile over the years. As described earlier research and development activities have kept integrated in the production organizations and every production organization has its own R&D/E department at Sandvik. Since offered products are so versatile and differ from each other in many ways it is natural that production sites have their own special knowledge areas.

In these circumstances global supply department saw a demand to harmonize design practices over the organization. This thesis was initiated as a pre-study to estimate DFMA utilisation possibilities and to develop common DFMA rules and guidelines for the company. Within this context the study for the DFMA rules and guidelines was started.

4.2 Design organization

Sandvik's product designing is organized into new product designing and current product designing. Generally each PDC´s engineering departments are further divided into mechanical, hydraulic, electrical and automation engineering. Main tasks, issues and responsibilities of these parties are shortly described next.

New Product Design, NPD, is responsible of the physical and product structure designing of new products. NPD is responsible of the new product offering and functions designing until 0-serie, hereafter the responsibility will be transferred to current product designing.

Current Product Engineering, CPE, is responsible for the maintaining of the currently sold machines. Product's large range and variation sets challenges for maintaining operations. Therefore it is important that New Product Design focuses on designing products that could be updated and maintained independently. In addition often multiplier effect of design changes is strong, because of complex product structures. One small change may result several consequences on different product structure levels which have to be coped with.

Mechanical engineering is responsible to create and maintain all product structures. Other design parties produce content to the product structure from their own special knowledge areas.

Hydraulic engineering is mainly responsible for a system design of hydraulics. It works with close collaboration with mechanical engineering. For instance layout design and component division is conducted by mechanical designing.

Electrical engineering assembles each machine's electrical module individually based on production order. With current technical solutions this procedure has been found to work. For instance, drill rigs have a much variation due to electrical functions. and there exists enormous amount of theoretical alternatives for electrical modules. Thereby, it has been perceived that it is easier to engineer every electrical module individually than try to define every possible variant beforehand.

Automation engineering is responsible for the software designing. One challenge for automation engineering is how to combine old traditional logic control systems, used with some products with new software into a single maintainable system.

4.3 The need for DFMA

The demand survey for common DFMA rules and guidelines was started by interviewing production and design representatives mainly at Tampere and Turku production sites. General manufacturing and assembly issues were discussed and reviewed how these issues have been taken into account in designing processes. In these discussions it was also attempted to find fresh ideas and opinions, how work methods could be developed and DFMA aspects could be considered in designing. It was also discussed which kind of tools could be useful and enable to improve manufacturing and assembly friendly designing. The focus was on the following questions: How to find and exploit the best design knowledge in the organization? How to avoid repeating previously encountered mistakes and problems?

In these meetings with designers the need for unify design processes were generally indentified. Also the importance to emphasise manufacturing and assembly issues on product designing were widely admitted. However, it emerged immediately that the right detail level and the usability of design guidelines would be a challenge. Generic design guidelines were met with doubt and especially the usefulness and usability was questioned. More favourable attitude among designers was achieved within the idea to share best design practices in form of examples and lessons learned cases. Examples and lessons learned could be used to share best design practices among different PDCs. This kind of knowledge sharing was thought to possess a demand for. Each production site has own special areas of knowledge and there exists for sure possibilities to enhance and support information exchange among sites.

Production engineers and personnel's opinions were pretty similar kind of. Lot of opportunities to develop products manufacturability and assemblability issues were recognised and problem areas were detected. A true need for DFMA existed. However, the creation of design rules and guidelines to support manufacturing and assembly issues was seen to be problematic. In addition, it revealed that production is not used to, nor familiar to set design requirements beforehand. This is natural, since normally feedback is collected in prototyping phase with liaison of engineering department. In this way production is not used to set design requirements beforehand. Hence, it was concluded that in the first version of the DFMA rules and guidelines the focus could be put to express production requirements to engineering department.

General DFMA issues that relates to Underground Mining's products are summarised in Appendix 1. Issues are classified into the four different design levels, accordingly to Institute for Product Development. Proposal actions and tools to cope with these issues are presented.

4.4 Detected development areas

Product's assemblability

Assemblability problems faced with Sandvik Underground Mining products are largely converging and similar kind of. Problems are largely related to the three main issues, huge amount of different product variants, module interfaces and assembly access.

Large amount of optional equipments are offered and products can be customised in numerous ways, especially with drill rigs. Large variation sets challenges for assembly operations. For instance, hose and wire routings cannot be standardises, assembly access and clearances may remain insufficient and lead to a tight assemblies according to machine's customization and chosen optional equipment. Origin of the problem relates to the options management, which has been conducted in a poor way without an overall plan. Product options have been designed and added among the years. New features and sub-systems have been added and hung with little consideration to entirety. For this reasons it is common that unwanted adjusting and tailoring work is needed in productions to fix and match chosen optional equipments to work together. Moreover, products have been assembled as a one station assembly for a long time. The flexibility of the one station assembly has allowed keeping all the product variants even if the customers were not interested in them. Generally, optional equipment are guilty for a substantial amount of confusion on the shop floor. Consequently a modular architecture requirement is set for all new products to enable line assembly. In addition, the amount of variants needs to be reduced from the final assembly and the work caused by the optional equipment needed to be removed from the final assembly line to the module and sub-assemblies.

To enable products' better line assemblability more attention should be paid to the product structure and module interfaces. As an ideal state production would like to prefer functional product structure, where module interfaces are clearly defined and which allows a wide utilisation of separately assembly and testable modules and sub-assemblies. However, modular product structure and module interfaces are faced with major challenges currently. Definition of clear mechanical, hydraulic and electrical module interfaces and product architecture are complicated and a major issues. As a one example of the current situation the front module of the production drill rig (DL-series) requires x hours to assembly. However, a similar amount of work hours is needed on the final assembly to attach this module to the drill rig. Current product structure and architecture leaves a lot to desire. Numerous development projects relating to the product structures are ongoing.

Assembly access and difficult working postures forms a third problem field. Assembly access is often a compromise and secondary design objective, since space constraints are often tight and external dimensions of underground machines are strictly predefined. However, it was apparent that assembly access and working postures should be considered in more detail and the awareness towards these issues should be enchased in designing. Furthermore, tight assembly access causes often a need for special tools.

For instance special tools are regularly needed with tight hydraulic assemblies, where assembly clearances are often so tight that special filed wrenches are needed. Particular working postures examination was decided to be excluded from this thesis since this was already in progress in Turku production site simultaneously.

Product's assemblability should be considered in early design phases

Saarenrinne studied in his Master's thesis at Sandvik Mining and Construction in 2009 an approach to create and analyze an assembly process of a new product simultaneously with the product's architectural design. He presented that the products' architectural design is the key factor in DFA process. The architecture of the product determines largely the production processes. Assembly order is basically determined by the architecture as well as the possibility to create sub-assemblies. Several decisions that have effect on the assembly strategy are made already in the architectural design phase. To understand these restrictions the assembly design need to be conducted simultaneously with the architectural design. Furthermore, it is crucial to understand the effect of these decisions already during the architectural design phase. [Whitney 2003;Saarenrinne 2009, p.1–2]

As a result of Saarenrinne's project it was noticed that the early creation of assembly order and assembly line creates good ground for the assemblability considerations. Well designed product architecture enables easy assembly directions and the assembly work can be divided into several separate sub-assemblies, which makes the final assembly faster. The shorter assembly time enables better customer service due to shorter delivery time. The work in process inventory decreases and thus costs involved in the production decreases. Moreover, architectural decisions are easier to evaluate with an assembly plan. Component division into sub-assemblies and modules is easier when functional interfaces are well defined. The definition of module interfaces furthers the assembly task and order creation and thus, it should be made in the beginning of the architectural design. [Saarenrinne 2009, p.51–52]

According to Saarenrinne the close cooperation of design team and production is crucial. The designer of the architecture should work in close connection with production to enchase mutual interaction. To ensure the feasibility of the design, regular meeting between production and design team needs to be arranged.

Common design reviews

Common design reviews are important to make sure that all necessary design issues have been considered designing. Systematic design reviews with production should be taken into part of the product development process. It would be advantageous to have a common design review with production personnel in early design phases. By this procedure more broad assemblability and manufacturability review could be enabled. For example the assemblability points of views of cable and hose routings could be more closely evaluated on these reviews. The earlier the review could be conducted the better chances for design changes exists. Nonetheless the review of the assemblability is also more challenging and requires expert knowledge of attendees to be able to estimate assemblability points of view on based on early sketches and drawings.

Design reviews are not at all a new thing, but systematic way to conduct and execute these reviews were lacking. Many times these reviews are not conducted until on prototype phase, when encountered assembly problems are reviewed with production personnel and necessary changes to design are dealt with. Common design reviews could thereby be conducted also on the earlier design phases when design changes are relatively easier to undertake.

Physical location of designers

As a one example to quickly solve encountered design related problems in production, designers can be physically moved near production to answer engineering change requests. Turku production site has applied this in practice. In Turku two mechanical designers were moved physically to work in a close collaboration with production to support the start of the line assembly of LH514 loader. Observed and handled problems and change requests are usually relatively small, but can cause lot of delays, extra work and unnecessary actions. Problems may relate for instance to missing and undocumented holes and threads, or optional instruments which are rarely used.

Arrangement has been successful and a lot of positive feedback has been received. Earlier design department were unable to handle all change requests, mainly because of the resource lack. In addition, change request handling usually requires that designer have to get familiar with the situation and physically check the situation. Moreover, it have been noticed that more and better quality feedback is received with this procedure. Production personnel are more familiar to make change request to the right people than engineering change requests via PDM system. Based on positive experiences acquired in Turku, Tampere production site has also initiated a new electrical engineering vacancy to support production operations and to solve quick change requests. However, it has to be noted that this procedure is more like a fire fighting against design problems and not a proactive way to tackle these issues.

Cost consciousness

For instance electrical design department would like to have more specific knowledge of the durations of certain assembly operations. At the moment design department is mostly able to do design decisions based on direct material costs and rough estimates of required assembly time. Engineering department would like to have more specific knowledge of the durations of different assembly tasks and operations.

In addition, engineering department was willing to receive more precise feedback and information from the production concerning assembly times of alternative design solutions. More precise knowledge could be used for instance to set common assembly time targets for new design projects. Currently engineering department doesn’t regard information provided by the company’s ERP system sufficiently reliable enough to be utilised. Better understanding of how costs are incurred and knowledge of assembly operations durations could have large effects towards made design decisions. Prerequisite for this would be precise and reliable monitoring of assembly times in form of work-study.

For example production would like to favour more utilisation of multi-pin connectors, because this would reduce assembly time. Nonetheless multi-pin connectors are more expensive and thus cause more direct costs. However, designing doesn't have a specific knowledge of assembly time savings achieved by utilisation of multi-pin connectors. The estimation of the real cost saving potential was experienced cumbersome. Could real cost savings been achieved or only transfer between indirect and direct costs? Moreover, it has to be noted that cost optimization is not a simply task. It has to be considered what are the overall effects, for instance to the lead time and the amount of work in process. However, the need to achieve better cost consciousness was obvious.

Established design practices

Established design practices could be reviewed and challenged. For example, it could be questioned why some design tasks are not conducted earlier in product development project. Why some design tasks are conducted on the prototype phase on top of the machine? These design tasks could be reviewed and causes could be investigated more closely. What are the practical reasons behind well established design practices? Root causes could be reviewed and classified into technical and economical. Are reasons behind established design practices technical, for instance related to design tools? Or is it just not economical try to perform all design tasks before prototyping? Based on this review it could be assesses, if same of these tasks could be performed differently. For instance could utilization of some new design tools enable to avoid prototype phase designing and aid to design more finalized products.

4.5 DFMA rules and guidelines

The DFMA rules and guidelines was set to collect together specific design principles and harmonize design practices among Sandvik's Product Development Centers. The aim was to share knowledge of the best design practices, inspire and recalls how widely and deeply made design decisions affect. In addition, the DFMA rules and guidelines endeavours to support product designing in a way, that already known production and manufacturability anomalies could be avoided. The main focus is to aid new product designing, but guidelines could also be utilised with current product engineering projects.

The DFMA rules and guidelines defined as a result of this thesis project is not meant to be final or comprehensive version but more like a first development version, which will be supplemented and further developed. Thereby, the objective of the thesis was to create a practical framework and guidelines for further development and collect together of manufacturability and assemblability issues that should be considered on product designing. Furthermore, beyond the scope of the thesis was to generate and initiate an environment where a cross-functional teams work together to optimize the product design. Especially, by encouraging design and production departments to work in more close cooperation.

During the thesis it relived that many other DFX areas are so close related and extremely important to the Sandvik's product designing that those cannot be ignored. For this reason the DFMA rules and guidelines were structured in a way to enable and serve later addition and development of other important design for abilities, for instance, testability, serviceability, logistics and safety considerations. This did not cause major changes. The structure was modified to allow later additions and supplementation concerning other DFX abilities. More specifically these issues are beyond the scope of this thesis and thereby excluded from this paper.

The structure and the contents of the DFMA rules and guidelines were under careful consideration. The instructions were wanted to be easy to use and easily maintainable and updatable. Furthermore, far-reaching design consequences were pursued. Successful DFMA utilisation in conceptual design phase normally leads to significantly simpler product structure and design. Thereby, it was wanted to underline the significance of early product development decisions, in order to eliminate major manufacturing problems already in conceptual design phase. The following figure 4.1 present sections, tools and issues involved into the instructions. Altogether these tools and sections form the DFMA rules and guidelines.

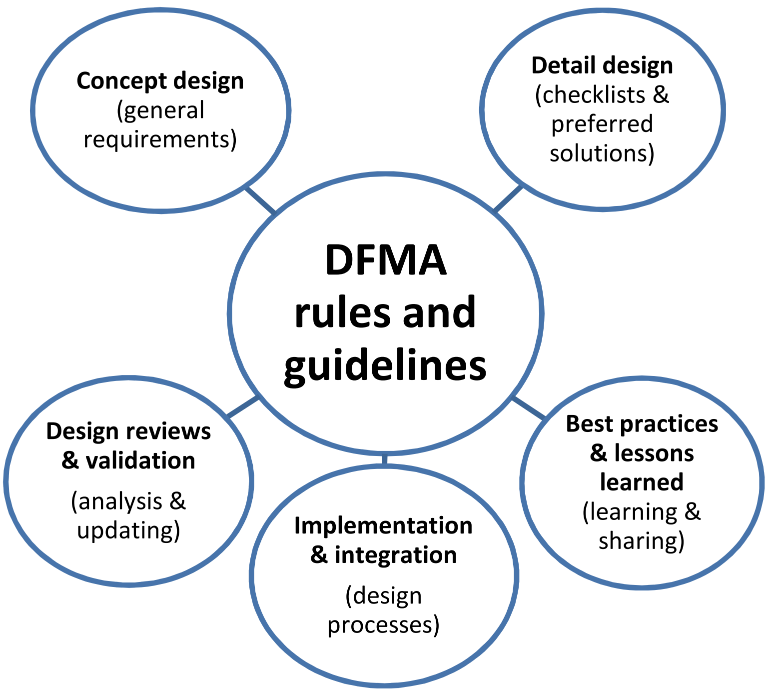

Figure 4.1. *Contents and tools of the DFMA rules and guidelines.*

Presented rules, guidelines and checklists in the first version were not intended to be used in an absolute manner, but rather as efficient tools, to ensure that various DFMA aspects have been considered in designing. Accordingly design guidelines were not intended to be a how-to-design manuals, but rather as a list of reminders to help to verify that critical design considerations have been made and that adequate and essential detail information has been provided. Next, the content and sections of the DFMA rules and guidelines are described with some examples.

Concept design

A concept design section was created to emphasise the meaning of early design phases. The architecture and early conceptual design of the product determines largely the production processes and thereby it is crucial to understand the effect of these decisions already during the early design phases. According to Whitney's classification presented in the theory part this section could be classified about as DFX in the large. Section thereby deals with issues that require consideration of the product as a whole, rather than individual parts in isolation, and likely will require consideration of the context in the factory, supply chain, distribution chain, and the rest of the product's life cycle.

Utilised tools on the concept design section:

- General design objectives and requirements for engineering departments.
- Introduction of selected DFX abilities and generic design principles.
- Generic design guidelines and examples.

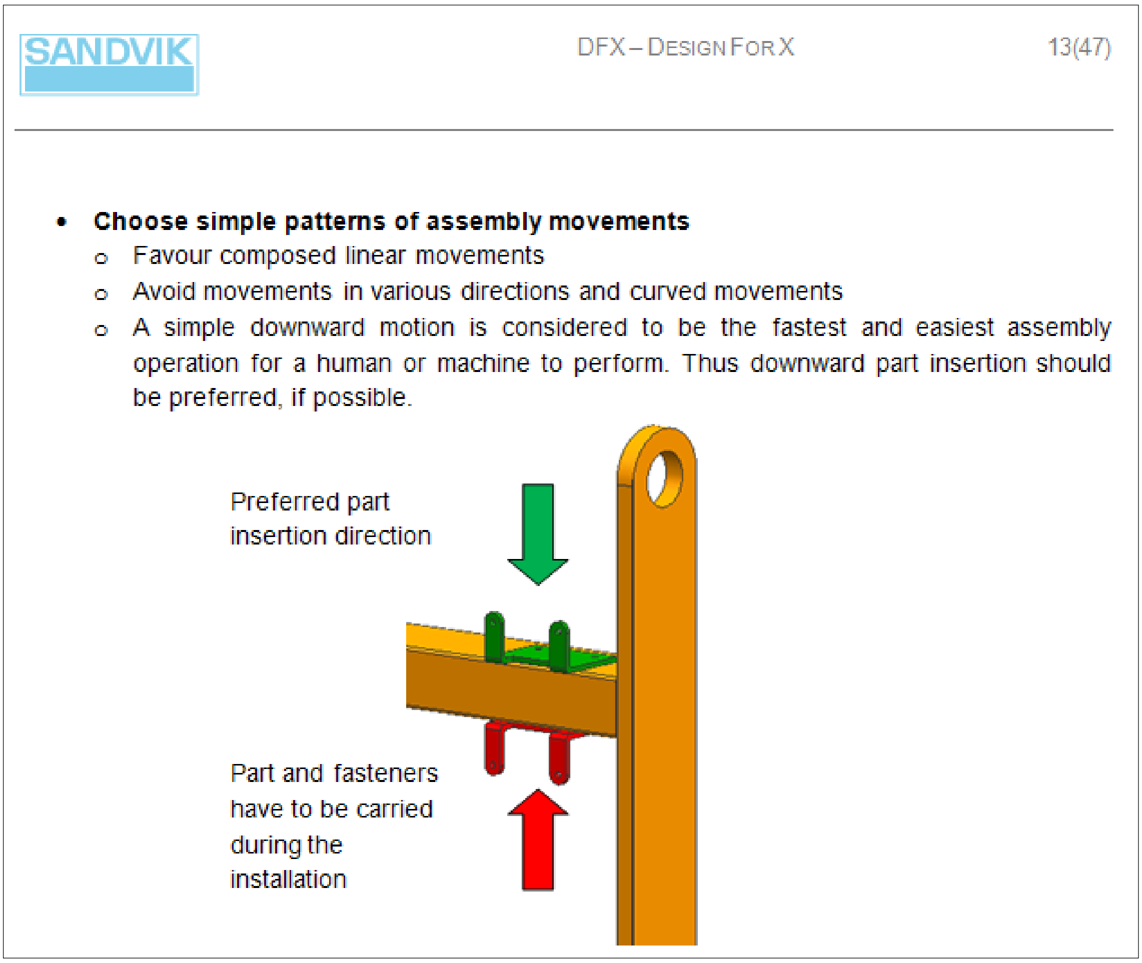

Figure 4.2. *Example from the DFMA rules & guidelines: a generic design guideline.*

Detail design

A detail design section was created to present production requirements and preferences. For instance by presenting preferred assembly clearances and layouts. According to Whitney' classification this section could be roughly classified as DFX in the Small. The section mostly focuses on the methods or process steps that can be applied to one part at a time by an engineer working alone. This section was meant to be supplemented later on to cover all necessary regarded critical design objects. On the first version critical components were indentified and roughly grouped under mechanical, hydraulic, electrical and automation engineering areas.

Utilised tools on the detail design section:

- Checklists to ensure consideration of various design aspects.
- Production preferences for critical components and preferred design solutions.

4.1.1. Cable and Hose Routing

Designing

- ☐ Routing design is conducted in collaboration with other engineering and production departments
- ☐ "On-top- of- the- machine" designing is avoided. Engineering work is as ready as possible before prototyping.

Assembly

- ☐ Assembly accessibility been examined from the whole length of the route
- ☐ Need for special assembly instructions has been considered (Look alike pictures are helpful for production)
- ☐ Cable/hose routing is documented
- ☐ Cable features; type, flexibility, space need and bending radius have been considered
- ☐ Reference and fastening points for the route are defined
- ☐ Enough amount of fasteners have been used to support the routing
- ☐ Movements of the joints have been considered
- ☐ Inlets' sharp edges have been considered (Bending radiuses of cables and hoses)

Serviceability

- ☐ Maintenance accessibility has been ensured
- ☐ There is no need for special tools

Safety

- ☐ Routing is protected against external forces (Shocks, impacts, abrasive wear)
- ☐ Hydraulic, electric and fuel routes are insulated from each other
- ☐ Routing is protected against water and moisture
- ☐ Thermal insulation has been considered (Engine heat, outdoor temperature)

Figure 4.3. *Example from the DFMA rules & guidelines: part of the cable and hose routing checklist.*

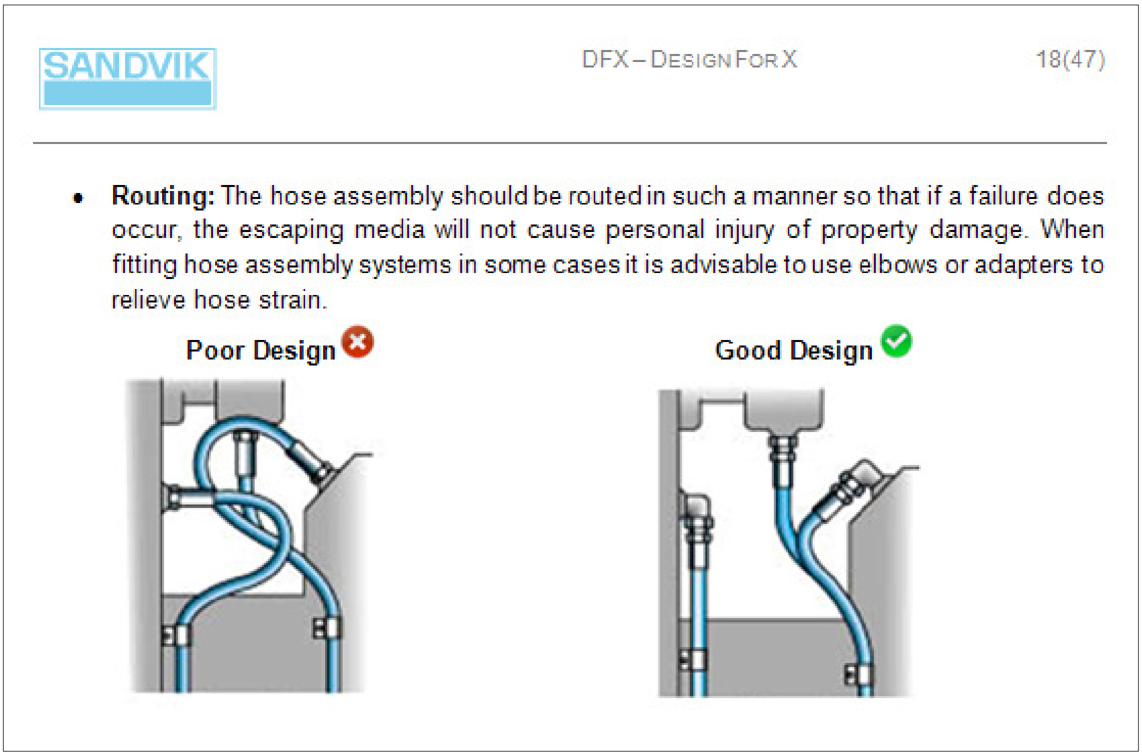

Figure 4.4. *Example from the DFMA rules & guidelines: preferred hose routing manner.*

Design reviews & validation

Design reviews & validation is essential part of the efficient utilisation and maintenance of the DFMA rules and guidelines. Design reviews are meant to be sessions where DFMA issues are commonly reviewed and discussed with production representatives and designers. First and foremost the DFMA rules and guidelines are updated and maintained from the necessary parts in these design reviews.

Utilised tools and processes:

- DFX abilities evaluation tool. (Sandvik's tool for quantitative DFX analysis)

Best practices & lessons learned

Best practices and lessons learned were aimed to share knowledge among PDCs in a documented form. A section was meant to be used for learning and sharing purposes. Aiming to exploit and take advantage of the explicit knowledge acquired in earlier product development projects. Toyota product development system's *learning* and *continuous improvement* was regarded as a role model for this [Liker 2004, Liker & Morgan 2006].

5.2.2. Hydraulic Pipe/Hose lesson learned with Underground Loaders

3D-modelled hydraulic pipe and hose routings

Turku production site has 3D-modelled hydraulic pipe and hose routings of underground loaders. 3D-modelling is conducted by production in Turku. Look alike pictures are very useful for assembly operations and with 3D-models the assemblability access can be examined beforehand.

E.g. Pictures from

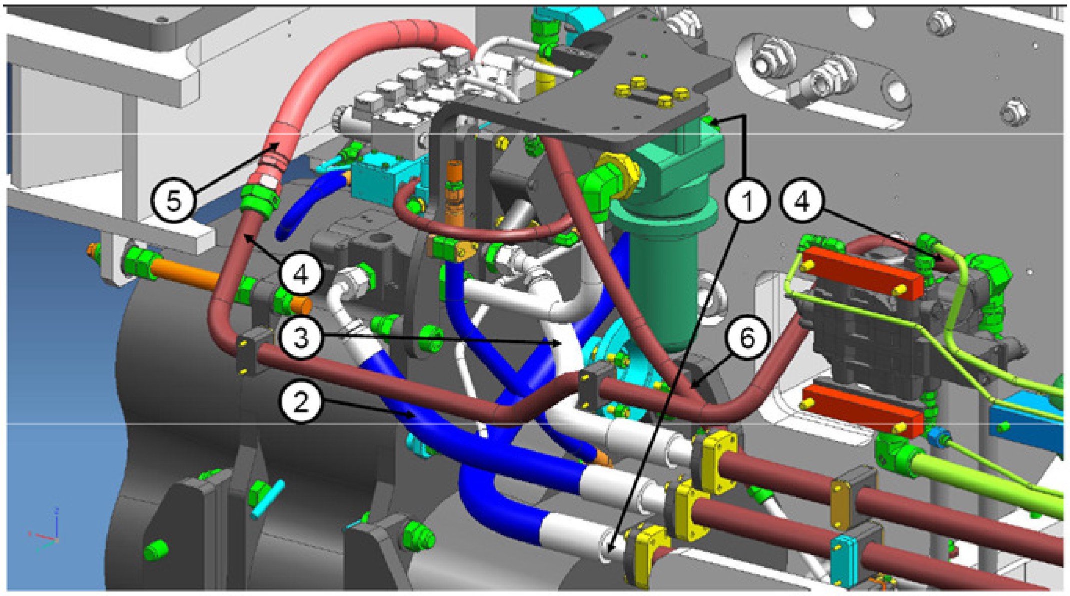

Figure 4.5. *Example from the DFMA rules & guidelines: sharing best design practices.*

Implementation and integration

Section focuses on to the integration of DFMA into the product development process. DFMA is aimed to be built into the basic development process to create opportunities to learn from every product development project. DFMA utilisation process was defined to ensure that manufacturing and assembly issues will be included and integrated into the product development process. In the first implementation stage, aim is mainly to support and develop collaboration procedures between design and production departments.

Utilised tools and processes:

- DFMA Verification and Validation process to integrate DFMA into Sandvik's design processes.
- Proposal procedure to conduct DFMA workshop in order to enchase collaboration between design and production departments.

4.6 A proposed DFMA system for the company

As a part of the thesis it was considered necessary to outline how the DFMA rules and guidelines integration into design processes and DFMA management more broadly could be arranged at Sandvik Underground Mining. To survey for this a questionnaire was conducted to the management of the PDCs, see Appendix 2. Based on this survey, literature review and multiple discussion following process descriptions were created.

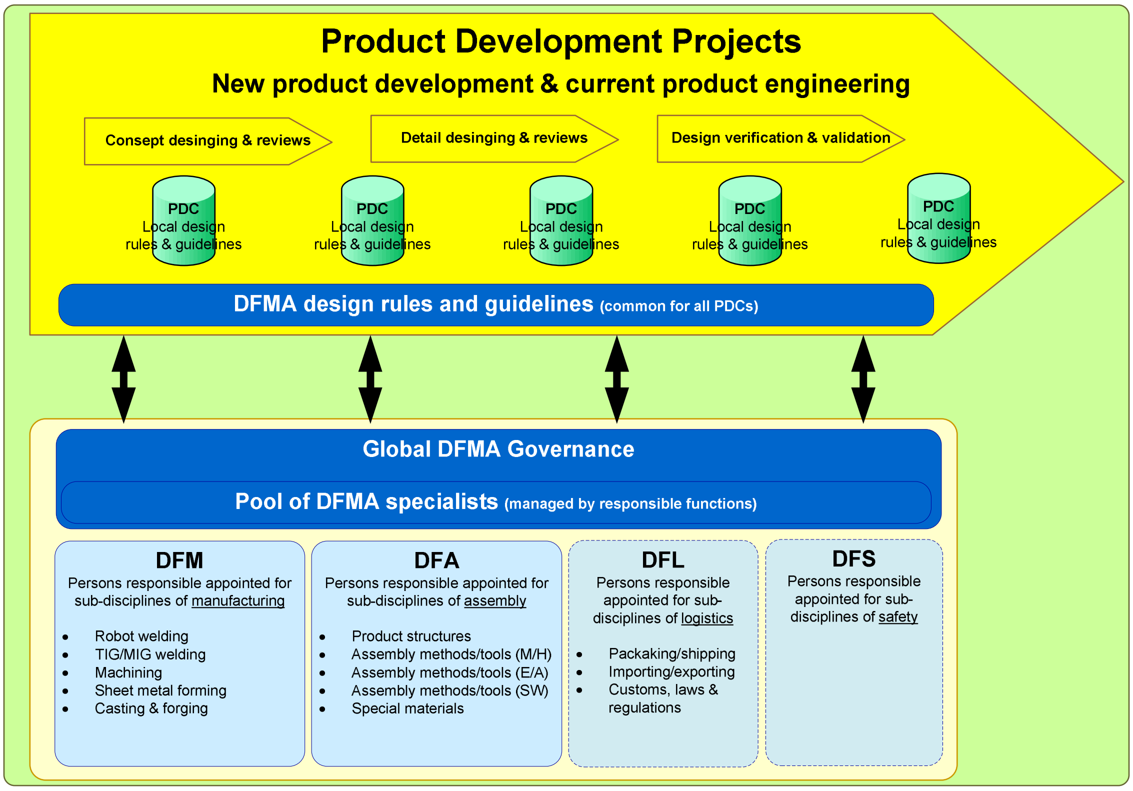

Figure 4.6. *Proposal DFMA system for the company.*

Figure 4.6. illustrates how the DFMA system can be arranged and integrated into the company's product development projects. A yellow arrow in the figure represents a product development project. The product development project has both PDC specific local guidelines and the common DFMA rules and guidelines to obey. This solution was seemed to be the most appropriate since the overall harmonization of design guidelines is estimated to be a vast project. A large amount of PDC local design rules and guidelines existed in the company and the management of these guidelines was conduct with varying ways. In addition, it was discovered that these guidelines are partially overlapping and in some cases even conflicting with each other. It was concluded that the harmonization work has to be conducted in manageable pieces. For this reason it is proposed that at the first stage of the DFMA implementation, the global DFMA rules and guidelines are not intended to replace but supplement existing local product specific design rules and guidelines. DFMA is aimed to be integrated into the company's existing management and quality system and thereby not to become a parallel system.

Planned DFMA system is based on the sharing of the best design knowledge and know-how across the organization and external suppliers. PDCs are specialised into varying issues and have differing competence areas. By DFMA this knowledge is aimed to be exploited more efficiently in product development process. Moreover, the proposed DFMA system relies on DFMA specialists who would be globally available to be utilised in product development projects. DFMA specialists are for instance experienced employees, production teams or suppliers who have expertise knowledge regarding specific manufacturing or assembly operation. DFMA specialists can then be utilised and allocated into product development projects to provide the best know-how into the use of design team. DFMA specialists can be utilised on any stage of the product development project, from conceptual designing to verification and validation phases. For instance, by providing specific manufacturing method knowledge to be utilised on material and process selection or by providing and challenging ideas on the conceptual designing phase when design changes are still relatively easy to make. Positive experiences exist from this kind of collaboration in the company. However, there were no tools or processes defined to systematically exploit this know-how. For instance, remarkable cost reductions were achieved, when Turku and Tampere PDCs were collaborating regarding frame welding of drill-rigs. Tampere PDC has outsourced all welding operations and lacks expertise of robot welding requirements. In contrast, robot welding is one of the competence areas of Turku PDC. In collaboration with Turku PDC frames were redesigned and optimised to serve better robot welding requirements and significant manufacturing cost reductions were achieved.

It is suggested that global DFMA governance is established to manage and administrate this pool of DFMA specialists. This requires that a company-wide systematic DFMA competence review has to be carefully conducted to survey the differing competence areas and to appoint responsible specialists. However, first the company wide DFMA knowledge level has to be improved and local DFMA pilot projects have to be conducted to demonstrate the power of DFMA. After that the arrangement of governance is relevant and specialists can be appointed. Recommended roadmap for DFMA implementation is presented on Appendix 3. To become viable, management's full commitment is required and enough resources have to be allocated to manage and further develop the DFMA system. Later on the system could be extended to consider other DFX abilities, illustrated by dashed line boxes in the figure 4.6.

4.7 DFMA integration into the design processes

The DFMA process describes how DFMA specialists and the defined DFMA rules and guidelines could be utilisation and integrated into product development processes.
Product development team and DFMA specialists are presented on the leftmost column in the figure 4.7. The DFMA rules and guidelines are nominally owned by supply function. This is opposed to many literature sources, which typically places the ownership of DFMA into the product development. [Whitney 2004, Fabricius 2003, Mottonen et al.

2009] The decision concerning ownership of the global DFMA rules and guidelines was made, since the priority in the first stage of the DFMA implementation was set to present production needs, requirements and preferences to R&D/E and to improve overall collaboration practices among these functions.

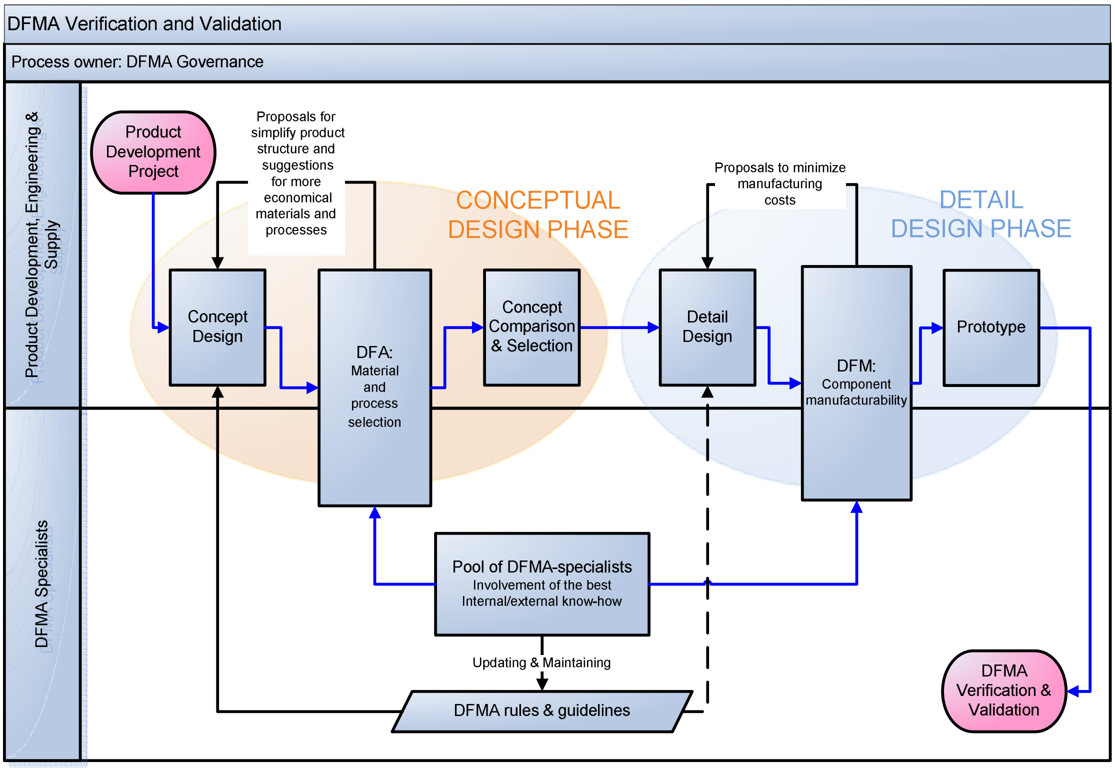

Figure 4.7. *DFMA Verification and Validation process. The process provides a schematic idea how the DFMA rules and guidelines can be utilised in product development projects. The process highlights the importance of early design phases and encourages into the cross-functional team work throughout the product development project.*

The DFMA rules and guidelines were divided into generic and product specific sections to efficiently support the wide and versatile product range of the company. Moreover, the division into generic and product specific sections was done to support the implementation among different PDCs and then to enhance the likelihood of successful implementation.

The updating and maintenance of the DFMA rules and guidelines is described in the figure 4.7. It is proposed that the generic section could be maintained and further developed by appointed DFMA specialists. The responsibility to maintain common design rules and guidelines of specific design area could this way be allocated to the party who has the best knowledge of it. The product specific section is proposed to be updated and maintained by a product development team for instance as a part of design reviews. Design reviews are integral part of the product development processes and defined to be situation were products' manufacturability and assemblability considerations are commonly reviewed. However, currently these reviews are conducted in relatively late design phases, typically during prototyping. Thus, the influence possibility into the product design is considered to be relatively low in these reviews.

Verification and validation of DFMA is known to be problematic area. The results of product development and utilisation of DFMA method are not easily measured and they are realized during the production of designed product long after the design process has been finished. Thereby, a long term commitment is required. [Saarenrinne 2009, p.51] According to Eskilander, the lack of economic proof is one the main barrier why companies are not using DFMA more widely. There exists no reliable way to show how much money a specific company could save if working with DFMA. It all depends a lot on how good the product design is today and how well a DFMA method can be implanted. [Eskilander 2001, p.33]

However, the management expressed a strong need for monitoring. For this purpose a preliminary quantitative DFMA analysis tool has been developed in the company a few years ago. However, mainly because of resource lack this tool has not been widely adopted to use. The tool is originally meant to be used at a product level to identify and evaluate DFX development objects. As a part the study it was estimated that this tool could be further on developed to draw up a rough baseline of the current design status. This baseline could be later on used to monitor the progress on various DFX areas. However, this requires that the tool is further on developed and utilised on more detailed level. This far DFX analysis have been conducted at a product level, which is a way too coarse and rough level to efficiently identify development objects and areas. To provide applicable and valuable information analysis tool should be used to evaluate smaller entities, for instance modules or sub-assemblies. Further on development work is thus needed with the analysis tool.

5 CONCLUSIONS

Underground mining business has long been a niche market, where the main focus has been to satisfy specific customer requirements in a best possible way, largely by tailoring product offering. There has been no coercive demand to enhance and consider further manufacturing and assembly issues in designing. Traditionally product's manufacturability has been left to the production department. However, tougher global competition and lead-time reduction targets have set a real need to consider these issues in product designing.

Definition of the applicable DFMA rules and guidelines for engineering is an extensive and interesting task. It was soon discovered that the work associates strongly with scattered information. Manufacturing knowledge is scattered in different parts of the organization and a lot of manufacturing and assembly knowledge is tacit by its nature. Moreover, it quickly became clear that deep expertise knowledge is required in many fields of engineering to fully understand the circumstances and backgrounds beyond the made design decisions. Generally detailed definition of design rules and guidelines is a problematic issue. Simple design rules and principles are often too general for any given problem and therefore not accepted or useful for designers. To be useful, design guidelines need to be concrete and case-related, but at the same time they should be generic enough to be commonly exploitable. The number of the rules is also problematic, because the more rules there are, the more problematic it becomes to select and prioritise them. In addition, design rules easily collide with each other and compromises have to be done. To cope with these issues, different types of checklists were utilised. Checklists do not tell us how specific design problem should be solved or which principle should be applied. Instead, they aim to ensure that various design aspects have been considered on designing. Consequently, it could not be described as a simple task to collect and parse information about design guidelines. A strong need for a framework to compile and sort DFMA information was recognized.

The most important design decisions that have an effect to a product's manufacturability are made in early design phases. The architecture of the product largely determines the production processes. For instance, assembly order is basically determined by the product architecture as well as the possibility to create sub-assemblies. The product's architectural design is, therefore, the key factor in DFMA. Consequently, it is crucial to understand the effect of early design decisions. The DFMA rules and guidelines were thus divided into two sections to efficiently support both the early conceptual designing and the later detail designing. The concept section deals with issues that require consideration of the product as a whole, and thereby is likely to require consideration in the larger context. The detail design section was created to present production requirements and preferences for critical components and parts. In addition, the DFMA rules and guidelines were divided into generic and product specific design instructions to efficiently support the wide and versatile product range of the company. The division into these sub-disciplines was done to support the implementation among different PDCs and then to enhance the likelihood of successful implementation and integration into engineering processes.

An obvious need for closer cooperation between design and production departments was identified. It was found that *a brick wall syndrome* existed in some form between design and production departments. Slightly exaggerated products are designed on one side of the wall and produced on the other. Information exchange between these function was discovered to be not efficient enough. Encouragement to work with cross-functional teams could help to improve this. Common DFMA workshops and pilot projects could provide fertile opportunities to develop the collaboration practices between these functions. Furthermore, it revealed that the production team is not used to express its design expectations and requirements beforehand. This is natural, since normally the team gives feedback afterwards in the prototyping phase. It was concluded that in the first stage of the DFMA implementation the focus should be put on expressing production requirements and preferences to the design department. In addition, it was recognised that there is a need to enhance feedback collection towards made design decision. Currently production feedback is collected with various ways regarding PDCs. The feedback mainly concerns poor design and urgent design changes. Hence, feedback collection and cooperation between design and production can be enhanced to cover recommended and preferred design solutions.

As a part of the thesis it was considered necessary to outline how the DFMA rules and guidelines integration into design processes and DFMA implementation more broadly could be arranged at Sandvik Underground Mining. For this purpose a proposal DFMA system for the company was introduced. The proposed DFMA system relies on experienced employees and their know-how. It is suggested that global DFMA governance is established to manage and administrate the pool of DFMA specialists in the company. In a longer term it is planed that a system to collect and share best design practices is established and built into the basic development processes to create opportunities to learn from every product development project. Toyota product development system's *build in learning* and *continuous improvement* was regarded as a role model for this. The proposed DFMA system is meant to supplement and become a part of the company's existing management and quality system. A fundamental goal of the DFMA utilisation is to seek a company-wide attitude change towards more integrated and comprehensive product development practices. It is clear that a change in underlying attitude takes time and a lot of further work is needed. Many advantages and benefits sought by the DFMA will be materialized over a long period of time and are not easily measurable.

The overall success is heavily dependent on how well DFMA will be accepted as a collective tool among different functions and PDCs. In a large organization this closely relates to the ownership relations and incentives. All parties should experience DFMA as their own in order to enable continuous development and utilisation. A proper DFMA training will be essentially important to assure and promote employees of the advantages provided by DFMA. Moreover, enthusiastic and committed employees have a key role to introduce and adopt DFMA into further development. Careful selection of the pilot DFMA project is also extremely important. DFMA method cannot be fully implemented once in company's all product development projects, see appendix 3. According to Institute for Product Development, local success story is desired to show what kind of results could be achieved with DFMA and to support wider implementation. Pilot project selection must be done carefully, since a failure in this might upset the implementation of DFMA for years and ruin the possibilities for further implementation. Ideally the pilot project should be important and the object of the project should be a typical product. The need for an improved design should be apparent to all people involved.

Studying a larger amount of companies is a potential topic for further research. This could enable interesting comparison and increase the reliability of the study. Moreover, it will be very interesting to see how the DFMA implementation will proceed in the case company.

6 FURTHER DEVELOPMENT IDEAS

DFMA implementation could be linked to the lean project
Wide production's lean project has been running on Sandvik Underground Mining last couple of years. According to lean principles this project has been focused on to minimize non-value-adding waste from manufacturing processes. According to Liker these eight major types of non-value-added wastes are: [Liker 2004, p.28–29]

1. Overproduction
2. Waiting
3. Unnecessary transport
4. Overprocessing or incorrect processing
5. Excess inventory
6. Unnecessary movement
7. Defects
8. Unused employment creativity

At the moment lean project has been progressed to the point where production begins to be pretty familiar with lean principles and the level to recognize development targets have been arisen among employees. Accordingly, DFMA could be marketed as a tool to eliminate waste from design and thereby as a natural continuation to the lean project. By this way, DFMA extends lean thinking to concern design activities. Following quotas are from designing news. [Stackpole 2010]

"Nine times out of 10, waste is designed right into the product - it's not something that occurs when the design gets to the production side."

”*The benefit of DFMA is that you look at a design before it's released to manufacturing and get rid of a lot of waste.”*

“There's a lot of effort on lean manufacturing to improve the whole process, but with that, you're really only making minor tweaks to the real problems that were introduced back at the design stage.”

Jeffrey Liker, the writer of Toyota Way, emphasises, that to be effective lean thinking cannot stop at shop floor. Thereby, lean management principles must extend beyond the shop floor in the product development and other company processes. [Liker & Morgan 2006] Generally lean product development aims to achieve very similar kind of results as DFMA. Both methods are customer oriented and utilise cross-functional teams for comprehensive problem solving. Moreover these methods emphasise the meaning of doing the things right at the first time and thereby avoiding very costly downstream design changes. On this basis DFMA rules and guidelines could be introduced as a lean tool for continuous improvement and to enhance cross-functional teamwork.

Concept evaluation framework and procedure

Concept evaluation framework could be developed to ensure comprehensive concept comparison. Evaluation criteria for concept comparison could be defined in collaboration of all possible stakeholders to ensure comprehensive comparison. Commonly utilised concept evaluation framework would emphasise the meaning of conceptual designing and would courage to bet more on development of alternative concepts. Weight factors could also be defined for decision criteria, in accordance their relative importance. Common concept evaluation framework would enable converge evaluation and supports and encourages the search for new design solutions. Checklist for conceptual design issues presented as a part of the DFMA rules and guidelines could be utilised as a starting point and extended to cover all necessary seemed evaluation criteria.

Moreover, if seemed applicable, framework could be extended to consider the whole conceptual designing process. Preliminary proposal how DFMA workshops could be conducted is presented on Appendix 4. Proposal is based on *A seven step procedure for DFM* presented by Institute for Product Development. [Fabricius 2003]

Utilisation of work-study and Standard Operation Procedures, SOP

Precise work-study of assembly operations and tasks could provide valuable information to support design decision. It was seen that designing department would like to receive more precise information from the production concerning assembly times of alternative design solutions. At the moment, in many cases designing doesn't regard information provided by production management system sufficiently reliable and accurate enough to be efficiently utilised on designing.

Careful work-study could provide a more specific knowledge and ground for design decisions. Better cost understanding and cost consciousness level among designers could be pursued. In addition work-study could reveal targets where development and redesigning could have the best pay off. Redesigning resources could then be allocation more efficiently, where most needed. More precise knowledge could also be used to set common targets for assembly times on new design projects.

Better understanding of how costs are incurred and knowledge of assembly operations durations could have far-reaching effects. Prerequisite for this would be precise and reliable monitoring of assembly times in form of work-study. In this study single work steps durations and sub assemblies assembly times should be clarified. Work-study could be conducted as a part of a creation of Standard Operation Procedure, SOP. SOPs are currently under development in many production sites as a part of the lean project.

An SOP is a written document or instruction detailing all steps and activities of a process or procedure. SOP includes detail work descriptions and work steps durations to enable monitoring and standardisation of the process. SOPs can be used as training materials for new operators and staff education. SOPs can be useful in solving production problems and moreover be used in continuous improvement initiatives in operations.

Assuming SOPs information could be gathered in a reliable way it could become a valuable source of information for both production and design departments. Production engineers could use SOPs to monitor and develop production processes and designers could use information provided by SOPs to support decision-making between alternative designs and thus consider production point of views better than previously. Thereby in accordance with lean principles accurate and reliable SOPs could be utilised to eliminate waste from both production and product designing.

Common 3D-modelling principles and guidelines

Common 3D-modelling principles and guidelines should be defined to enhance design reusability and compatibility. Common procedure and practice could enable a better product structure and variant management on designing by providing better compatible design models. Common modelling principles and guidelines would also support to harmonize varying design practices among different PDCs.

Furthermore tools for assembly access examinations could be reviewed and utilised if seemed applicable. For instance, possibilities to 3D-model cable and hose routes or software to enable electrical harness designing on top of the 3D-model could be assessed and harmonised to the use of all PDCs. These practices would enable to design more finalised products and reduce the design work amount needed on prototype phase.

For instance Antti Haanpaa has studied in his master thesis best practices for assembly modelling in a Teamcenter and NX context. Similar kind of definition of best design modelling practices would be useful for Sandvik. Following issues could be considered: [Haanpää, 2010]

- Component positioning and orientation in assemblies.
- Utilisation of component groups. Groups of components could be managed as a whole. For example, the hydraulic system designer can upload the lightened product model, where only the hydraulic system components are fully presented.
- Assemblies loading preferences.
- Choice of prudent modelling context. A three-dimensional model within the modelling task is carried out. (Product hierarchy, concurrent engineering, revision management etc.)
- Utilisation of geometrical dependencies between parts. (Feature transmission)

More comprehensive prototyping

A prototyping phase could be threatened more carefully. The prototyping phase is considered to be too short and conducted too quickly at the moment. During the thesis it was discovered that is not realistic to require that all engineering work should be completed before prototyping. Many complex entities cannot be entirely designed before prototyping with current engineering tools. For example hydraulic hose or electrical wire routings cannot be fully finalized before actual prototype is built. Generally speaking even in some cases, for instance possibilities to design more finalized hose routings where identified it was not seemed overall beneficial. The costs and resource usage was estimated to be much larger than the gained utility.

For these reasons more careful and systematic prototype phase could tackle many DFMA related problems before production ramp-up. Even it is not an optimal solution and DFMA strongly aims to influence earlier in the product development process than prototyping, the procedure could provide significant advantages. Production personnel are much more familiar to give feedback on based on actual prototype and could therefore be involved more efficiently to product development. In addition, important serviceability and maintenance issues could be considered more carefully in prototyping phase, if more resources and time can be provided to prototyping phase. At the moment there is not enough resources allocated to prototyping and schedules are experienced to be too tight to enable comprehensive development work. Even DFMA emphasizes the meaning of early design decisions more careful and systematic prototyping could supplement the overall product development process. More comprehensive prototype building and analyzing could ensure a smooth transition into production and then decrease the amount of further design change requests.

Design review checklist

DFMA considerations that should be checked on predefined design reviews could be collected in a form of checklist. Checklists provided by a draft version of DFMA rules and guidelines could be used as a basis to develop this tool. Reviews should be conducted both on conceptual design phase and on detail prototype phase with all concerning stakeholders, including engineering, production, purchasing, quality etc. functions. Review checklists could be customised by products to enable review of varying product characteristics and to ensure adequate level of detail. Moreover, a general list of attendees could be defined to ensure that all necessary stakeholders are represented on these reviews.

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Interviews and discussions

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Sami Järventausta, Engineering Manager
Paula Kainu, Global Development Engineer
Tero Kankkunen, Production Development Engineer
Anssi Kouhia, Project Engineer
Jari Lepistö, Engineering Manager
Henri Lod, Production Engineer
Pertti Lyytikäinen, Product Engineer, Mechanics
Teemu Majander, Design Engineer, Mechanics
Jenni Mustonen, Quality Manager
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Antti Pulkkinen, University Lecturer

APPENDIX 2. DFMA QUESTIONNAIRE

Design For Manufacturing and Assembly (DFMA) competence questionnaire

Name:
Title:
Site:

1. What are your PDC's strongest competence areas in manufacturing technologies and assembly methods and why? (E.g. robot welding, TIG/MIG welding, boring, machining, thin plate forming, casting, forging, electric wiring, hydraulic hose/pipe routing, mechanical installations, joining, tools/equipment, product structures, instructions)

2. What are the most critical manufacturing technologies & assembly methods considering your products and why? (E.g. robot welding, TIG/MIG welding, boring, machining, thin plate forming, casting, forging, electric wiring, hydraulic hose/pipe routing, mechanical installations, joining, tools/equipment, product structures, instructions)

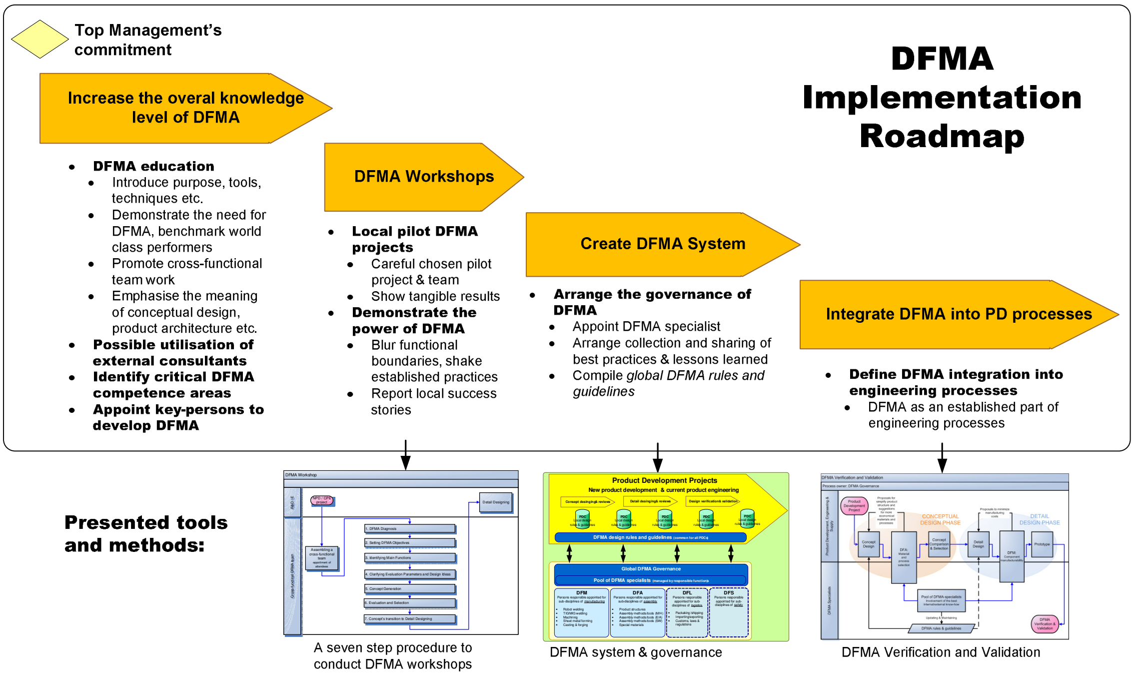
3. Estimate your PDC's ability to offer manufacturing technology and assembly method knowledge and know-how to other PDCs and other product groups globally in critical competence areas? (Collaboration practices currently and in future with other PDCs?)

4. Estimate your PDC's ability to use globally appointed DFMA specialists (internal or external) in product development projects to review your concept and/or detail designs? What are main challenges to use external resources for reviews? (DFMA specialists with best know-how from special area of expertise)

5. Estimate your PDC's ability to gather, analyse, deliver and receive manufacturing and assembly requirements? Are manufacturing and assembly requirements and preferences clear and detailed enough? How collaboration between production, suppliers and engineering could be enhanced?

APPENDIX 3. DFMA IMPLEMENTATION ROADMAP

Appendix presents a proposal roadmap for DFMA implementation in a company context. Top management's commitment is seen as a prerequisite for the implementation.



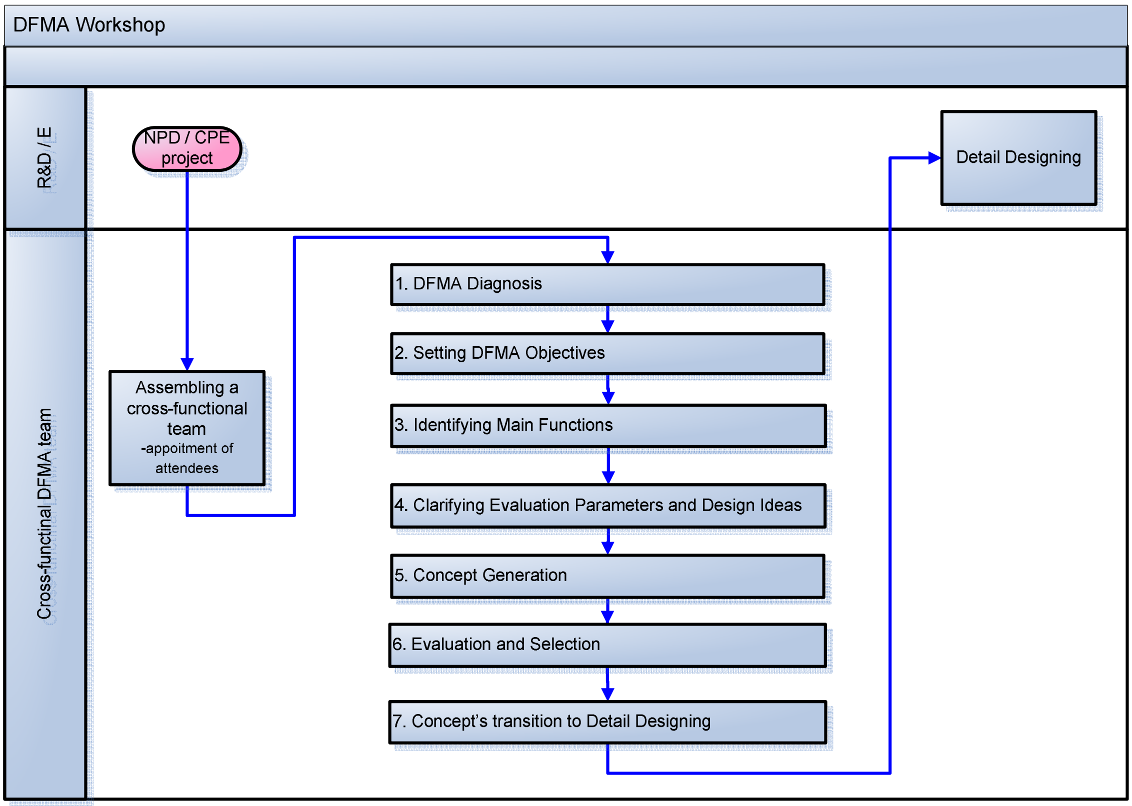
APPENDIX 4. DFMA WORKSHOPS

Appendix gives a proposal procedure how cross-functional DFMA workshops can be conducted.

Key Points

- Must have a multi-functional team. DFMA aims to enchase cooperation between design and production departments. Appointment of attendees: designers, production engineers and personnel, quality, supply, purchasing, cost specialists etc.
- Use an independent facilitator. No ownership in designing and can keeps flow of workshop moving.
- Educate team on workshop procedures and DFMA principles.
- Needed preparation work
  - Preliminary study of manufacturing and assembly flows and operations.
  - Baseline the current design. Team needs to understand where we are now. Provide an overview description of manufacturing and assembly operations.
  - Have some type of cost baseline to perform trade-off studies.
  - Break system down into manageable pieces and conduct multiple workshops.
- Careful selection of the pilot DFMA project
  - DFMA method cannot be fully implemented once in company's all product development projects. It should be planned to be implemented in small steps to make it more manageable.
  - The right selection of first project is particularly important. It should neither be too ambitious nor too modest.
  - The objectives, tools and techniques to use for the pilot project have to be commonly selected and agreed.

A proposal procedure how to conduct DFMA workshop



Illustrated procedure presents how DFMA workshops could be conducted to reduce the risk of omitting important activities in DFMA project and to help the design team to carry out activities on optimal sequence. Procedure has seven steps and follows *a seven step DFM procedure* introduced by Institute of Product Development from Technical University of Denmark. (Fabricius 2003)

Tasks involved to each step are collected and presented to the following check-list. The checklist can be used to support the management of DFMA workshops. Procedure can be modified and applied as seen fit in accordance to the design project.

Checklist's purpose is:

- to reduce the risk of omitting important activities.
- to help design team carry out activities in an optimal sequence.
- to make it easier for management to supervise the project and monitor progress.

Step 1. DFMA Diagnosis

- ☐ Clarify which product families are offered and how they differ from each other and from competing products
- ☐ Clarify which basic products variants are offered within each product family, and examine options offered as standard or extra equipment
- ☐ Clarify already implemented modularization and standardization efforts
- ☐ Check the present manufacturability & assemblability
    - ☐ Check the direct (variable) production costs
    - ☐ Check types and size of indirect production costs (overhead costs)
    - ☐ Examine the problems related to product quality in production
    - ☐ Analyze the flexibility of present product/production
    - ☐ Clarify particular production risks embedded in the product design
    - ☐ Examine production lead time
    - ☐ Examine the delivery time
    - ☐ Analyze efficiency concerning utilization of critical assets (investments, floor space etc.)
    - ☐ Check the critical environmental consequences of the present production (work hazards)
- ☐ Compare the performance of present product in the areas mentioned above with the competing products
- ☐ Compare key value performances to the competitors (e.g. performance/cost ratios such as Watt/€)

Step 2. Setting DFMA Objectives

- ☐ Clarify DFMA objectives
    - ☐ Specify objectives for direct costs
    - ☐ Specify objectives for overhead costs
    - ☐ Specify high priority areas concerning of quality conformance
    - ☐ Specify the desired flexibility of the future manufacturing & assembly
    - ☐ Clarify the production risks that are especially important to eliminate in the future
    - ☐ Specify the future production lead time
    - ☐ Specify future delivery time
    - ☐ Specify desired future productivity
    - ☐ Clarify the priority of the objectives above
    - ☐ Clarify key value objectives

Step 3. Identifying Main Functions

- ☐ Clarify all the main functions of the product, including optional product functions
- ☐ Clarify the boundaries of the product system and the mutual interaction between the various main functions (Module interfaces)

Step 4. Clarifying Evaluation Parameters and Design Ideas

- ☐ List evaluation parameters used for assessing design ideas:
  - ☐ List manufacturability/assemblability drivers for each main function
  - ☐ List critical technical requirements for each main function
- ☐ Find innovative alternative DFMA ideas realizing each main function

Step 5. Concept Generation

- ☐ Clarify the basis of the accumulated design ideas and the objective priorities, a number of ideal concepts. E.g. the overhead-cost-ideal or the lead-time-ideal product concept to showing extreme solutions
- ☐ Generate a number of more realistic all-round concepts in accordance with DFMA objectives
- ☐ Check that alternative conceptual designs for their conformance with the basic product specification
- ☐ Check that the alternative conceptual designs do not compromise the customer experienced product quality in critical areas

Step 6. Evaluation and Selection

- ☐ Compare alternative conceptual designs in the areas of the DFMA objectives
  - ☐ Compare expected direct production costs
  - ☐ Compare expected overhead production costs
  - ☐ Compare expected differences within quality conformance
  - ☐ Compare differences in manufacturing/assembly flexibility
  - ☐ Compare risk elements embedded in the designs
  - ☐ Compare expected lead-time in production
  - ☐ Compare differences in possible delivery time
  - ☐ Compare differences in expected productivity
  - ☐ Calculate the investment necessary for each alternative
- ☐ Check and compare market potential of alternative designs
- ☐ Select the best conceptual product design
- ☐ Check that savings/improvements are sufficient for justifying the investment
- ☐ Check that the product quality is in accordance with the requirement of all stakeholders
- ☐ Check that all participants in the development team fully understand the chosen conceptual design
- ☐ Check that management fully understands the implications of the new conceptual design

Step 7. Concept's transition to Detail Designing

- ☐ Check that detail design does not compromise the conceptual decisions:
  - ☐ Check that standardization of components is sufficiently high

- ☐ Check that each of the component designs are suitable for the chosen production process
- ☐ Check that all detailed design provides acceptable assembly and test operations